LOCOMOTIVE EMISSION STANDARDS

Regulatory Support Document

United States Environmental Protection Agency
Office of Mobile Sources

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NOTE TO READERS

This document is a revised version of the December 1997 Regulatory Support Document that was placed in the public docket at the time of signature. This version includes editorial revisions, corrections, and some additional information. The technological feasibility, environmental, and economic analyses are unchanged in content. The electronic version of this document also contains tables and figures that were included in the hard copy of the December 1997 document, but were not included in the electronic version.

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1.0 Industry Background

The regulations for locomotives and locomotive engines are expected to directly impact four industries. These industries are: 1) manufacturers of locomotives and locomotive engines (original equipment manufacturers (OEMs)); (2) owners and operators of locomotives (railroads); 3) remanufacturers of locomotives and locomotive engines (OEMs, railroads, independent remanufacturers); and 4) suppliers of locomotive parts (OEMs, railroads, independent remanufacturers, parts manufacturers). A brief overview of these directly impacted industries follows, along with descriptions of the general economic impact of railroads on the nation and current regulation of railroads.

1.1 Locomotive Manufacturing

Locomotives used in the United States are primarily produced by two manufacturers: the Electromotive Division of General Motors (EMD) and General Electric Transportation Systems (GETS). EMD manufactures its locomotives primarily in London, Ontario and their engines in La Grange, Illinois. The GETS locomotive manufacturing facilities are located in Erie, Pennsylvania, while their engine manufacturing facilities are located in Grove City, Pennsylvania. These manufacturers produce both the locomotive chassis and propulsion engines. They also remanufacture engines. MotivePower Industries (formerly MK Rail Corporation) has produced some locomotives using engines manufactured by Caterpillar, Inc. The Peoria Locomotive Works also manufactures locomotives using Caterpillar Engines, and Republic Locomotives manufactures locomotives powered by Detroit Diesel Corporation engines. The Cummins Engine Company, Inc. also produces engines which may be used in locomotives.

1.2 Railroads

In the United States, freight railroads are subdivided into three classes based on annual revenue by the Federal government's Surface Transportation Board (STB). The STB is an adjudicatory body that was formed in 1966 to settle disputes and regulate the various modes of surface transportation within the U.S. Organizationally a part of the Department of Transportation, the STB deals with railway rate and service issues, railway restructuring and various other issues, including classification of railroads. (STB regulations for the classification of railroads are contained in 49 CFR Chapter X.) In 1994 the STB classified a railroad as a Class I railroad if its annual revenue was $255.9 million or greater, as a Class II railroad if its annual revenue is between $20.5 and 255.8 million, and as a Class III railroad if its annual revenue is less than $20.5 million. The Class I railroads are the nationwide, long-distance, line-haul railroads which carry the bulk of the railroad commerce. In 1994, there were 12 Class I railroads operating in the U.S. Due to recent mergers, there are currently 9 Class I freight railroads operating in the country. Class I railroads presently operate approximately 21,000 locomotives in the U.S. Class I railroads account for over 90 percent of the ton-miles of freight hauled annually and consumed 3.60 billion gallons of diesel fuel in 1996, which is about 91 percent of all locomotive fuel used in the U.S. Of these, the five largest Class I railroads, BNSF, CSX, Conrail, Norfolk Southern, and Union Pacific, account for the vast majority of the Class I locomotives currently in service in the U.S. (These five will soon be four, as Conrail is absorbed by CSX and Norfolk Southern.)

Statistics compiled by the Association of American Railroads (AAR) and the American Short Line Railroad Association (ASLRA) show that there are approximately 530 Class II and III railroads (not including commuter and insular railroads). A more detailed breakdown of these can be found in Table 1-1. They consist primarily of regional and local line-haul and switching railroads[1], which operate in a much more confined environment than do the Class I railroads. For example, the average length of haul for a regional railroad is 167 miles, while the average length of haul for a local line-haul railroad is 41 miles (as opposed to an average of about 800 miles for a Class I). Class II and III railroads operate approximately 4,200 locomotives.[2] All but about 400 of these are owned by the operating railroad. Over 85 percent of the locomotives owned by the Class II and III railroads were originally manufactured prior to 1973. Class II and III railroads use about 215 million gallons of fuel annually, about 6 percent of the total used by locomotives. These last two facts indicate that Class II and III railroads are responsible for less than one percent of all emissions from post-1972 locomotives.

Some of the smaller railroads are owned and operated by Class I railroads, many of which are operated as formal subsidiaries for financial purposes, but are run as standalone entities. In 1995, there were 222 local line-haul railroads and 253 switching and terminal railroads, including subsidiaries (regional and local railroads may also have subsidiaries). A few of these are publicly held railroads and some are shipper-owned. Insular in-plant railroads are not included in this total. ASLRA estimated that there are probably about 1,000 insular railroads in the U.S. These railroads are not common carriers, but rather are dedicated to in-plant use. They typically operate a single switch locomotive powered by an engine with less than 1000 hp. Such locomotives typically use a few thousand gallons of diesel fuel each year, and thus are not a particularly significant source of emissions.

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[1] "Regional railroad" and "local railroad" are terms used by AAR that are similar, but not identical, to "Class II" and "Class III", respectively.

[2] "Locomotive Data for Small Railroads," Memorandum, Charles Moulis, U.S. EPA, to public docket A-94-31, December 5, 1997.

Table 1-1

Profile of Railroad Industry - 1995 [3]

Type of Railroad	Number of Railroads	Year-end Employees
Class I Freight Railroad	9	185,762
Class I Subsidiaries	25	3,570
National Passenger Railroads	1	23,800
Commuter Railroads[4]	15	22,526
Regional Railroads	30	9,115
Local/Line-Haul Railroads	222	5,060
Switching & Terminal Railroads	130	1,805
Shipper-Owned Railroads	79	2,369
Government-Owned Railroads	36	1,092
Other/Mixed Ownership[5]	8	905
TOTAL	555	256,004

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[3] "Railroad Ten Year Trends", Association of American Railroads, 1995.

[4] Does not include all-electric railroads.

[5] Does not include insular railroads.

Amtrak is the sole large-scale provider of inter-city passenger transport. In their comments on the NPRM, Amtrak indicated that their fleet includes 315 diesel-electric locomotives, consuming 72 million gallons of diesel fuel annually, plus a number of all-electric locomotives operating in the Northeast corridor.[6] They offer service to 44 states, extending over 23,000 miles of track. With a few exceptions, most of the trackage upon which Amtrak trains operate is owned by the freight railroads. Based on gross revenue, Amtrak is classified as a Class I railroad by the STB. However, unlike the Class I freight railroads, Amtrak's current operating expenses exceed its gross revenue. There are also 15 independent commuter rail systems operating in 12 U.S. cities, consuming 61 million gallons of diesel fuel annually.[7] Finally, there are a handful of very small passenger railroads that are primarily operated for tours. These tourist railroads are included within the Class II and III railroads.

1.3 Locomotive Remanufacturers and Suppliers

While the original manufacturers provide much of the remanufacturing services to their customers, there are several smaller entities that also provide remanufacturing services for locomotive engines. Moreover, some of the Class I and II railroads remanufacture locomotive engines for their own units and on a contract basis for other railroads. EPA has been able to identify nine independent remanufacturers that are small business entities. Due to the necessarily limited demand, most of them find it advantageous to diversify their operations. Many of them remanufacture marine or other large diesel engines in addition to locomotive engines. A few apparently remanufacture locomotives primarily for resale or lease, while six of them remanufacture engines for operating railroads or industrial customers. Many of these six remanufacturers also manufacture or remanufacture locomotive engine components. A few also offer contract maintenance. This may be tied to a locomotive lease, or may be offered separately to owners of locomotives.

In addition to the above original manufacturers and remanufacturers, EPA has been able to identify fourteen independent suppliers and remanufacturers of locomotive engine components for use by railroads or by the independent remanufacturers. All but two are small business entities who produce and/or remanufacture locomotive engine components. Again, due to the limited size of the market, many of them produce and/or remanufacture other locomotive components (in addition to engine components) or components for marine or large industrial engines). Some of them also serve as locomotive wreckers and deal in used components.

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[6] Docket item #A-94-31-IV-D-28.

[7] "1996 Transit Fact Book", American Public Transportation Association.

It should be noted that railroad equipment is a broad general industrial category that includes such components as wheels and axles, traction motors, main generators/alternators, brakes, air compressors, governors and electronic controls and a host of other products and services related to railroad cars, as well as locomotive engines and components. It also includes services such as repainting and conducting required inspections. Many of the suppliers identified also deal in some of these other components and services as well as in locomotive engine components. None of these suppliers list railroad equipment as their primary or secondary business activity. The primary business codes that they do list range from "plating and polishing" to "turbines and turbine generators". Most list "industrial machinery and equipment", "internal combustion engine service" or "necessary repair services" as their primary or secondary business code.

1.4 Leasing

Locomotives are available for lease from OEMs, remanufacturers, and a small number of specialized leasing companies formed for that purpose. Leasing practices appear to be fairly standardized throughout the industry. Although lease contracts can be tailored on an individual basis, most leases seem to incorporate standard boilerplate language, terms and conditions. Under a typical lease, the lessee takes on the responsibility for safety certification and maintenance (parts and scheduled service) of the locomotive (including the engine), although these could be made a part of the lease package if desired. The lease duration ranged between 30 days and 5 years, with the average being 3 years.

As can be seen from the Table 1-2, the use of leasing has increased greatly in recent years among Class I railroads, with almost two-thirds of the locomotives placed in service in 1994 being leased. Leasing among Class II and III railroads is not nearly as widespread, with only about 5 percent of the total number of locomotives being leased.

Table 1-2

Purchase and Leasing of New Locomotives[8]
Class I Railroads Only

Year	Total New Locomotives	Number Purchased	Number Leased	Percent Leased
1985	522	430	92	18%
1986	280	173	107	38%
1987	131	110	21	16%
1988	356	320	36	10%
1989	609	523	86	14%
1990	534	417	117	22%
1991	472	273	199	42%
1992	323	213	110	34%
1993	504	379	125	25%
1994	821	288	533	65%

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[8] "Railroad Ten Year Trends", Association of American Railroads, 1995.

1.5 Locomotive Safety Regulations

Achieving and maintaining the safe operation of commercial (common carrier) railroads in the U.S. falls under the jurisdiction of the Federal Railroad Administration (FRA), which is a part of the Department of Transportation. The FRA was created in 1966 to perform a number of disparate functions, including rehabilitating Northeast Corridor rail passenger service, supporting research and development for rail transportation, and promoting and enforcing safety regulations throughout the railway system.

FRA safety regulations apply to railroads on a nationwide basis. These regulations require a safety inspection of each locomotive used in commercial operations every 92 days. The inspections are usually performed by the railroad which owns or leases the locomotive. FRA personnel review the findings of these inspections and any corrective actions identified and taken. Since each locomotive is required to be out of revenue service for inspection every 92 days, railroads commonly schedule their performance of preventive maintenance at these times. It appears likely that each locomotive is out of service for 12 to 24 hours during each FRA safety inspection and preventative maintenance period.[9] To limit the time that locomotives are out of service for these safety inspections and preventive maintenance, railroads maintain suitable facilities distributed across the nation. Thus, it appears that the railroads have had a long history of compliance with federal regulations, and have developed strategies to live within the regulations and to minimize any adverse business impacts that may have resulted.

1.6 Commercial Role of Railroads

Current railroad networks (rail lines) are geographically widespread across the United States, serving every major city in the country. Approximately one-third of the freight hauled in the United States is hauled by train. There are few industries or citizens in the country who are not ultimate consumers of services provided by American railroad companies. According to statistics compiled by AAR, rail revenue accounted for 0.5 percent of Gross National Product in 1994. Thus, efficient train transportation is a vital factor in the strength of the U.S. economy.

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[9] Values are an approximate estimate by FRA personnel.

In order for Class I railroads to operate nationally, they need unhindered rail access across all state boundaries. If different states regulated locomotives differently, a railroad could conceivably be forced to change locomotives at state boundaries, and/or have state-specific locomotive fleets. Currently, facilities for such changes do not exist, and even if switching areas were available at state boundaries, it would be a costly and time consuming disruption of interstate commerce. A disruption in the efficient interstate movement of trains throughout the U.S. could have an impact on the health and well-being of not only the rail industry, but the entire U.S. economy as well.

Rail transport currently holds about 41% of the market for inter-city freight ton-miles. The remaining segments of this market are accommodated through other modes of transport, including trucking (27%), river canal/barge (11.5%) and pipeline (18%) of total ton-miles. Rail is a primary means of transport for many bulk commodities, such as chemicals (26%), autos (65%), coal (55%) and grain (26%).[10] Being a primary source/mode of transporting these items, the railroad industry normally sets the industry standard price ($/ton-mile). Rail transport is typically more fuel efficient and less expensive than other land-based sources of transport. In terms of BTUs of energy expended per ton-mile of freight hauled, Department of Energy statistics indicate that rail transport can be as much as seven times more efficient than truck transport. The AAR has asserted that one double-stack train can carry the equivalent of 280 truckloads of freight.[11]

Figure 1-1 and Table 1-3 show the long term growth trends for the amount of freight carried by Class I railroads and the amount of fuel consumed in carrying that freight.[12] As can be seen from these data, the ton miles of freight carried have more than doubled, while total fuel consumption has remained relatively constant or decreased slightly. The reason for this is that locomotive manufacturers have made continual progress in reducing the fuel efficiency of their engines and the electrical efficiency of their alternators and motors. It is reasonable to project that the growth in the amount of freight hauled will continue in the future. It is less certain, however, whether fuel consumption will increase significantly in the near future. (Note: the analysis of the environmental and economic impacts of this rulemaking assume no growth in fuel consumption.)

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[10] Association of American Railroad.

[11] Quoted from May 15, 1997 testimony by Bruce Wilson representing AAR. Docket item #A-94-31-IV-D-7.

[12] "Railroad Facts", Association of American Railroads, 1996 edition.

Table 1-3

Annual Fuel Consumption and Revenue Freight
For Class I Railroads

Year	Revenue Freight (Million Ton-Miles)	Fuel Consumption (Million Gallons)
1955	623,615	3,384
1960	572,309	3,463
1965	697,878	3,592
1970	764,809	3,545
1975	754,252	3,657
1980	918,958	3,904
1985	876,984	3,110
1990	1,033,969	3,115
1995	1,305,688	3,480

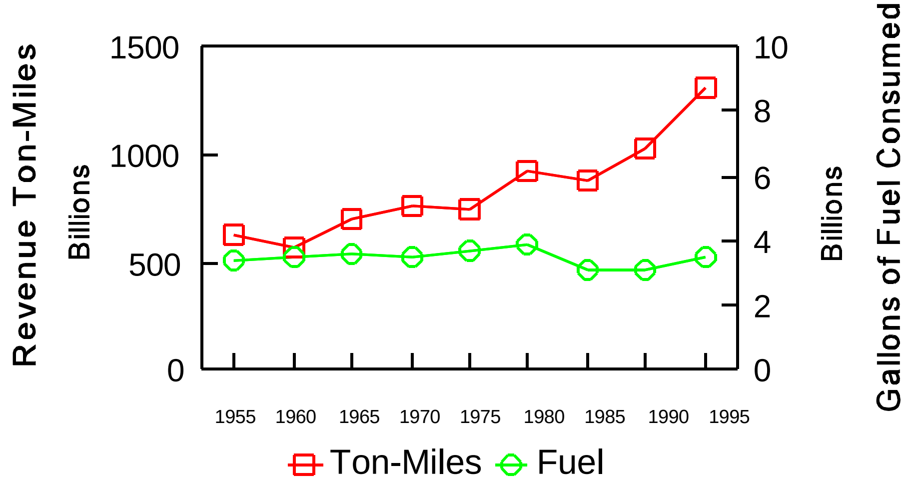

Figure 1-1 Fuel Consumption and Revenue Ton-Miles for Class I Railroads

1.7 Environmental Impacts of a Modal Shift

Another important point which required consideration in the regulation of locomotives is the potential for a modal shift. A modal shift is a change from one form of transportation, such as trains, to another form, such as trucks. Modal shift can have negative or positive effects on national and local emissions inventories. Negative modal shift occurs when there is a shift to a more polluting form of transportation. Thus, when negative modal shift occurs, the environment suffers.

Information currently available to EPA shows that truck-based freight movement generates more pollutants per ton-mile of freight hauled than current, unregulated rail-based forms of freight movement. Estimates quantifying the difference indicate that locomotives are on the order of three times cleaner than trucks on an emissions per ton-mile basis.[13] Other studies conducted in the U.S. and Canada have also concluded that freight transported by rail is three times cleaner than that transported by truck. For example, Department of Energy data show that HD trucks produce almost 2.5 times the quantity of NOx emissions as do railroads, but only account for 75 percent as many ton-miles of freight hauled.[14] Thus, any freight normally carried by rail that is instead hauled by trucks would increase the overall mass of emissions, even at current emissions rates.

Regulations that were overly stringent could raise equipment and/or operating costs to the point that it might be a wiser economic choice to move current rail freight by truck. A disruption in interstate commerce resulting from delays caused by changing locomotives at state boundaries, due to separate state locomotive regulations, could be costly to railroad companies. These increased costs would be reflected in the price of hauling freight by rail, and could even eliminate some rail carriers from the market. In both of these cases, customers would likely switch to the higher-polluting trucks for the movement of their freight. Overly stringent regulation of the rail industry or a disruption in interstate rail movement could therefore result in increases in the emissions inventory, through a negative modal shift. (Note: as is described in Chapter 7, EPA estimates that this rule will cost railroads about $80 million annually, which is about one-quarter of one percent of annual freight revenue for U.S. railroads.)

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[13] American Society of Mechanical Engineers, Statement on Surface Transportation of Intercity Freight, May 18,1992.

[14] U.S. DOE, Transportation Energy Book, Edition 16 (1994), 1996.

2.0 Locomotive Background

2.1 Energy Supply Sources for Locomotives

Locomotives may be subdivided into two general groups on the basis of the source of energy for powering the locomotive: 1) "all-electric" and 2) "engine-powered". In the "all-electric" group, externally generated electrical energy is supplied to the locomotive by means of a catenary or some other electrical transfer device. An example of this type of locomotive is commonly seen moving commuter trains. Power to operate the locomotive is not generated by an onboard engine. Emission control requirements for all-electric locomotives would be achieved at the point of electrical power generation, and thus are not included in this rulemaking.

In the "engine-powered" group of locomotives, fuel (usually diesel in the U.S.) is carried on the locomotive. The energy contained in the fuel is converted to power by burning the fuel in the locomotive engine. A small portion of the engine output power is normally used directly to drive an air compressor to provide brakes for the locomotive and train. However, the vast majority of the output power from the engine is converted to electrical energy in an alternator or generator which is directly connected to the engine. This electrical energy is transmitted to electric motors (traction motors) connected directly to the drive wheels of the locomotive for propulsion, as well as to motors which drive the cooling fans, pumps, etc., necessary for operation of the engine and the locomotive.[15] In the case of passenger locomotives, electrical energy is also supplied to the coaches of the train for heating, air conditioning, lighting, etc. (i.e., "hotel power"). In some passenger trains, electrical energy required for the operation of the passenger coaches is supplied by a locomotive-mounted auxiliary engine.

2.2 Hotel Power

As noted above, the design of locomotives for use in passenger train service provides for the locomotive to be operated in either of two distinct modes. In one mode, the locomotive engine provides only propulsion power for the train. In this mode, the engine speed changes with changes in power output, resulting in operation similar to freight locomotives. In the second mode, the locomotive engine supplies electrical "hotel power" to the passenger cars, in addition to providing propulsion power for the train. Hotel power provided to the passenger cars can amount to as much as 800 kW (1070 hp). In contrast to operation in the non-hotel power mode, the engine speed remains constant with changes occurring in power output when operating in hotel power mode. Thus, the two modes of operation utilize different speed and load points

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[15] Essentially all "engine powered" locomotives used in the U.S. employ a diesel engine and the electrical drive system described. The term "diesel-electric" has therefore become the most common terminology for these locomotives.

to generate similar propulsion power. These differences in speed and load points mean that locomotive engines will have different emissions characteristics when operating in hotel power mode than when operating in non-hotel power mode.

2.3 Types of Locomotives and Locomotive Design Features

Locomotives generally fall into three broad categories based on their intended use. Switch locomotives, typically 2000 hp or less, are the least powerful locomotives, and are used in freight yards to assemble and disassemble trains, or for short hauls of small trains. Some larger road switchers can be rated as high as 2300 hp. Passenger locomotives are powered by engines of approximately 3000 hp, and may be equipped with an auxiliary engine to provide hotel power for the train, although they may also generate hotel power with the main engine, as discussed above. Freight or line-haul locomotives are the most powerful locomotives and are used to power freight train operations over long distances. Older line-haul locomotives are typically powered by engines of approximately 2000-3000 hp, while newer line-haul locomotives are powered by engines of approximately 3500-5000 hp. In some cases, older line-haul locomotives (especially lower powered ones) are used in switch applications. The industry expects that the next generation of line-haul locomotives will be powered by 6000 hp engines.

Locomotives also vary with respect to size, similar to the variation in horsepower. Switch locomotives tend to be about 40 to 55 feet long, while line-haul locomotives are typically 60 to 70 feet long. Locomotive length is roughly correlated with engine size, and thus the difference in length has become more significant as locomotive engines have become larger and more powerful. Locomotive length is also related to the number of axles that a locomotive has. In the past, the typical locomotive had four axles (two trucks with two axles each). While, there still are a large number of four-axle locomotives in service, nearly all newly manufactured line-haul locomotives have six axles (two trucks with three axles each). There are two primary advantages of having more axles on the locomotive. First, with the additional axles, locomotives can be heavier, without increasing the load on each individual axle (and thus the load on the rail). Second, six-axle locomotives typically have greater tractive power at low speeds, which can be critical when climbing steep grades. Four-axle locomotives, however, are somewhat better for higher speed service. Nevertheless, it appears that the major railroads are attempting to standardize their fleets by purchasing six-axle locomotives almost exclusively. This is likely to lead to the future discontinuation of the practice of converting old line-haul locomotives into switch locomotives, since these larger six-axle locomotives are probably too long to be practical in most switch applications.

One unique feature of locomotives that makes them different than other, currently regulated mobile sources is the way that power is transferred from the engine to the wheels. Most mobile sources utilize mechanical means (*i.e.*, a transmission) to transfer energy from the engine to the wheels (or other point where the power is applied). Because there is a mechanical connection between the road vehicle engine and the wheels, the relationship between engine rotational speed and vehicle speed is mechanically dictated by the gear ratios in the transmission and final drive (e.g., the differential and rear axle). This results in engine operation which is very transient in nature, with respect to changes in both speed and load. In contrast, locomotive engines are typically connected to an electrical alternator or generator to convert the mechanical energy to electricity. As noted above, this electricity is then used to power traction motors which turn the wheels. The effect of this arrangement is that a locomotive engine can be operated at a desired power output and corresponding engine speed without being constrained by vehicle speed. The range of possible combinations of locomotive speed and engine power vary from a locomotive speed approaching zero with the engine at rated power and speed, to the locomotive at maximum speed and the engine at idle speed producing no propulsion power. This lack of a direct, mechanical connection between the engine and the wheels allows the engine to operate in an essentially steady-state mode, in a number of discrete power settings, or notches, which are described below.

Another design feature unique to railroad locomotive engines is the design and operation of the throttle. Power settings for railroad engines (throttle position) generally involve eight discrete positions, or notches, on the throttle gate, in addition to idle and the dynamic brake function (which will be considered later). Each throttle notch position is numerically identified, with notch position one being the lowest power setting, other than idle, and position eight being maximum power. Because of this design, each notch on the throttle corresponds to a discrete setting on the fuel delivery system of the engine. These are the only engine power settings at which the locomotive can operate. The net effect of this method of control is that the engines can operate at only eight distinct power levels for propulsion, and at idle and dynamic brake. Railroads and engine manufacturers have, however, indicated the possibility of either changing the number of throttle notch positions provided or eliminating throttle notches entirely in the future.

Dynamic braking is another unique feature of locomotives setting them apart from other mobile sources. In dynamic braking the traction motors act as generators, with the generated power being dissipated as heat through an electric resistance grid. While the engine is not generating motive power (i.e., power to propel the locomotive, also known as tractive power) in the dynamic brake mode, it is generating power to operate resistance grid cooling fans. As such, the engine is operating in a power mode that is different than the power notches or idle settings discussed above. While most diesel-electric locomotives have a dynamic braking mode, some do not (generally switch locomotives).

Another unique design feature of locomotives is the design of the engine cooling system and procedures used to control engine coolant temperature. Normal practice in locomotive design has been to mount the radiator on the top of the locomotive and not to use a thermostat. Control of coolant temperature is achieved by controlling the heat rejection rate at the radiator. The rate of heat rejection at the radiator can be controlled by means such as turning fans on and off or employing a variable speed fan drive, or by controlling the amount of coolant flow to the radiator (using non-thermostat controls). A related point of difference between road vehicle and locomotive engine cooling systems is that antifreeze is not generally used in locomotives. Many factors contribute to this design approach. The very large size of a locomotive engine causes both a very high degree of difficulty in starting the engine at low temperatures when the engine has cooled to ambient temperature, and a high probability that coolant leakage will occur during both warm up and cool down cycles. Because of problems inherent in starting these engines when allowed to cool to relatively low ambient temperatures, and the potential for engine damage due to leakage of coolant, locomotive engines tend not to be shut down for long periods of time, especially during cold weather. When the engines are shut down, restarts are generally performed before significant cooling of the engine occurs, to avoid or minimize restart problems and coolant leakage problems.

The final unique design feature noted here is the manner in which new designs and design changes are developed. The initial design of any new models/modifications and production of prototype models are done in much the same manner as is the case with other mobile sources. Locomotive manufacturers indicated that this process can be expected to require from 12 to 24 months for significant changes such as those required to comply with the new Tier 0 standards. Prototype locomotives are typically sold or leased to the railroads for extended field reliability testing, normally of one to two years duration. Only after this testing is completed can the new design/design change be certified and placed into normal production.

2.4 Maintenance

Locomotive maintenance practices also present some unique features. As is the case with other mobile sources, locomotive maintenance activities can be broken down into a number of subcategories. Routine servicing consists of providing the fuel, oil, water, sand (which is applied to the rails for added traction), and other expendables necessary for day-to-day operation. Scheduled maintenance can be classified as light (e.g., inspection and cleaning of fuel injectors) or heavy, which can range from repair or replacement of major engine components (such as power assemblies) to a complete engine remanufacture. Wherever possible, scheduled maintenance, particularly the lighter maintenance, is timed to coincide with periodic federally-required safety inspections, which normally occur at 92-day intervals. Breakdown maintenance, which may be required to be done in the field, consists of the actions necessary to get a locomotive back into service. Because of the cost of a breakdown in terms of lost revenue that could result from a stalled train or blocked track, every effort is made to minimize the need for this type of maintenance. In general, railroads strive to maintain a high degree of reliability, which results in more rigorous maintenance practices than would be expected for most other mobile sources. However, the competitive nature of the business also results in close scrutiny of costs to achieve the most cost-effective approach to achieving the necessary reliability. This has resulted in a variety of approaches to providing maintenance.

Maintenance functions were initially the purview of the individual railroads. Some major railroads with extensive facilities have turned to providing this service for other railroads, and a few of the smaller railroads also have done the same, in particular for other small railroads. However, the tendency in recent years has been toward a diversification of maintenance providers; a number of independent companies have come into existence to provide many of the necessary, often specialized services involved (e.g., turbocharger repair or remanufacture). The trend toward outside maintenance has also been accelerated by the policies of some of the larger railroads to divest themselves of not only maintenance activities, but ownership of locomotives as well. The logical culmination of this trend is the "power by the mile" concept, whereby a railroad can lease a locomotive with all the necessary attendant services for an agreed-upon rate.

2.5 Replacement Rates

Due to the long total life span of locomotives and their engines, annual replacement rates of existing locomotives with freshly-manufactured units are very low. EPA estimated a replacement rate for locomotives and locomotive engines based on historical data supplied by AAR, and from conversations with manufacturers and railroad operators. Table 2-1 illustrates the historical replacement rates for locomotives in the Class I railroad industry. From 1955 through 1995, annual sales of freshly-manufactured locomotives fluctuated significantly, but have averaged approximately 500 units over the last ten years. This replacement rate indicates a fleet turnover time of about 40 years for Class I railroads. Fleet turnover is the time required for the locomotive fleet to be entirely composed of locomotives that were not in service as of the base year. Although the percentage of new units in the fleet has increased significantly since 1994, it is too soon to determine whether this is a general trend or merely cyclical variation.

Table 2-1

Historical Replacement Rates for Locomotives[16]

Year	Total Locomotives in Service	Freshly Manufactured Locomotives Purchased[17]	Percent of Fleet which were Freshly Manufactured Units
1955	31,395	1,097	3.5%
1960	29,031	389	1.3%
1965	27,780	1,387	5.0%
1970	27,077	1,029	3.8%
1975	27,846	772	2.8%
1980	28,094	1,480	5.3%
1983	25,448	200	0.8%
1984	24,117	436	1.8%
1985	22,548	522	2.3%
1986	20,790	280	1.3%
1987	19,647	131	0.7%
1988	19,364	356	1.8%
1989	19,015	609	3.2%
1990	18,835	530	2.8%
1991	18,344	472	2.6%
1992	18,004	323	1.8%
1993	18,161	504	2.8%
1994	18,505	821	4.4%
1995	18,512	928	5.0%
5 year average		610	3.33%
10 year average		495	2.62%

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[16] Data are for Class I railroads only.

[17] Includes leased vehicles.

It should be noted that the above data apply to Class I railroads only. Similar data for Class II and III railroads were not available. Purchasing practices have historically been for Class I railroads to buy virtually all of the freshly-manufactured locomotives sold. As the Class I railroads replace their equipment with freshly-manufactured units, the older units are either sold by the Class I railroads to smaller railroads, are scrapped, or are purchased for remanufacture and ultimate resale (or leasing) by companies specializing in this work. The industry-wide replacement rate for locomotives would therefore actually be lower than those indicated for the Class I railroads only. This would mean that the time required for the total locomotive fleet to turn over would be longer.

Additionally, independent of cyclic changes in the industry, future locomotive replacement rates could actually decrease. Locomotive manufacturers are now producing locomotives that have significantly more horsepower than older locomotives. Railroads have requested this change so that fewer locomotives are needed to pull a train. Placing more horsepower on a locomotive chassis increases overall train fuel efficiency. For example, it would be more fuel-efficient to use two 6000 hp locomotives, rather than three 4000 hp locomotives, to pull the same weight train, because the weight of an entire locomotive can be eliminated. Thus, whereas three old locomotives may be scrapped, only two new locomotives may need to be bought as replacements.

On the other hand, the business outlook for the railroad industry has been improving in the last few years. As railroads have become increasingly cost-competitive, they are attracting more business. This in turn increases demand for locomotive power to move the additional freight. Thus, while purchases of new locomotives may increase in the next few years, these locomotives will likely supplement, rather than replace, existing locomotives. Moreover, if freight demands continue to increase, it may become cost-effective to operate locomotives for longer periods than are estimated here.

2.6 Remanufacturing

Since most locomotive engines are designed to be remanufactured a number of times, they generally have extremely durable engine blocks and internal parts. Parts or systems that experience inherently high wear rates (irrespective of design and materials used) are designed to be easily replaced so as to limit the time that the unit is out of service for repair or remanufacture. The prime example of parts that are designed to be readily replaceable on locomotive engines are the power assemblies(i.e., the pistons, piston rings, cylinder liners, fuel injectors and controls, fuel injection pump(s) and controls, and valves). Within the power assemblies, parts such as the cylinder head in general do not experience high wear rates, and may be reused after being inspected and requalified. The power assemblies can be remanufactured to bring them back to as-new condition or they can be upgraded to incorporate the latest design configuration for that engine. In addition to the power assemblies there are numerous other parts or systems that may also be replaced.[18] Engine remanufactures may be performed either by the railroad that owns the locomotive or by the original manufacturer of the locomotive. Remanufactures are also performed by companies that specialize in performing this work.

During its forty-plus year total life span, a locomotive engine could be remanufactured as many as ten times (although this would not be considered the norm). Locomotive engine remanufacturing events are thus routine, and are usually part of the scheduled maintenance. It is standard practice for the Class I railroads within the railroad industry to remanufacture a line-haul locomotive engine every four to eight years. Typically newer locomotives, which have very high usage rates, are remanufactured every four years. Older locomotives usually are remanufactured less frequently because they are used less within each year. Such remanufacturing is necessary to insure the continued proper functioning of the engine. Remanufacturing is performed to correct losses in power or fuel economy, and to prevent catastrophic failures, which may cause a railroad line to be blocked by an immobile train. The trend toward higher power locomotives is naturally resulting in a trend of fewer locomotives per train, thereby increasing the likelihood that a train would become immobilized by the failure of a single locomotive. Road failures are very costly to the railroads because the importance of timeliness to their customers, and the difficulty in getting replacement locomotives to the location of the failure.

When a locomotive engine is remanufactured, it receives replacement parts which are either freshly-manufactured or remanufactured to as-new condition (in terms of their operation and durability).[19] This includes the emission-related parts which, if not part of the basic engine design, are also generally designed to be periodically replaced. The replacement parts are also often updated designs, which are designed to either restore or improve the original performance of the engine in terms of durability, fuel economy and emissions. Because of a locomotive engine's long life, a significant overall improvement in the original design of the parts, and therefore of the engine, is possible over the total life of the unit. Since these improvements in design usually occur in the power assemblies (i.e., the components where fuel is burned and where emissions originate), remanufacturing of the engine essentially also makes the locomotive or locomotive engine a new system in terms of emission performance. A remanufactured locomotive would therefore be like-new in terms of emissions generation and control.

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[18] Bottom end components, such as crankshafts and bearings, are often remanufactured only during every other remanufacture event. Remanufacture events that do not include these bottom end components are sometimes referred to as "partial remanufactures"

[19] In some cases, some components are remanufactured by welding in new metal and remachining the component to the original specifications.

While Class I locomotives are remanufactured on a relatively frequent and scheduled basis of 4 to 8 years, Class II and III locomotives may be remanufactured on a longer schedule or may not be remanufactured at all. The typical service life of a locomotive (40 years) is often exceeded by small railroads that continue to use older locomotives. It is important to note that there is no inherent limit on how many times a locomotive can be remanufactured, or how long it can last. Rather, the service life of a locomotive or locomotive engine is limited by economics. For example, in cases, where it is economical to cut out damaged sections of a frame, and weld in new metal, an old locomotive may be salvaged instead of being scrapped. Remanufacturers can also replace other major components such as the trucks or traction motors, to allow an older locomotive to stay in service. However, at some point, most railroads decide that the improved efficiency of newer technologies justifies the additional cost, and thus scrap the entire locomotive. Nevertheless, many smaller railroads, especially switching and terminal railroads, are still using locomotives that were originally manufactured in the 1940s.

3.0 Emission Reduction Technology

This chapter provides an overview of emission reduction technology which may be used on locomotives. The first two sections are brief background discussions of locomotive pollutants and locomotive operating characteristics. The third section is an overview of technologies which EPA considered with respect to their potential to reduce emissions from locomotives. The last section is a discussion of those technologies that EPA believes will be both available and cost-effective by the time of the locomotive emissions standards are scheduled to take effect.

3.1 Locomotive Pollutants

The emission constituents of greatest concern from locomotive diesel engines are oxides of nitrogen (NOx), particulate matter (PM) and smoke. NOx is formed at high temperatures and pressures associated with combustion of fuel in the engine, when nitrogen in the air combines with available oxygen in the combustion chamber. PM generally results from incomplete evaporation and burning of the fuel droplets (and lubricating oil) in the combustion chamber. Thus, PM emissions are generally associated with low combustion temperatures, inadequate combustion air in the vicinity of fuel droplets, and fuel impurities. Since NOx formation is associated with high combustion temperatures and PM is associated with low combustion temperatures, many technologies and emission compliance strategies which reduce one tend to increase the other. Unburned hydrocarbons (HC) and carbon monoxide (CO) are generally emitted at low levels from properly functioning diesel engines due to the presence of excess oxygen which allows nearly complete combustion of these intermediate combustion products. Smoke emissions are typically caused by an inadequate supply of air for combustion during times of engine acceleration, or by low combustion temperatures. In general, technologies and compliance strategies that reduce PM emissions tend to reduce HC, CO and smoke emissions as well, although to differing degrees.

Ambient conditions also affect emission rates from diesel engines. Temperature and humidity can both affect NOx emission rates as a result of their effect on combustion temperatures. NOx emissions are higher at lower ambient humidity levels, and can be higher at higher ambient temperatures. While not as strong a relationship, the opposite effect is observed for HC and PM emissions which can be higher with lower combustion temperatures. Low barometric pressures, which occur at higher altitudes, can also cause higher smoke and PM emissions with some reduction in NOx.[20] At high altitudes, where the air is less dense, the engine draws a smaller mass of air, which can result in a lower air/fuel ratio. At such conditions, less oxygen is available for the combustion process, which results in less complete

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[20] Chaffin, C., Ullman, T., "Effects of Increased Altitude on Heavy-Duty-Diesel Emissions." SAE Paper 940669, 1994.

combustion of hydrocarbons, as well as increased PM and smoke emissions. This loss in combustion efficiency also results in lower temperatures which generally means lower NOx. This potential effect is most prevalent in non-compensated naturally-aspirated engines and less prevalent for turbocharger engines where fuel flow is adjusted for pressure changes. For naturally aspirated engines, higher altitudes can actually result in higher peak temperatures due to an increased ignition delay. This delay is due to a lower density in the cylinder, which leads to less frequent molecular collisions (between oxygen and fuel), and thus a slower reaction rate. However, the ignition delay is not observed in engines with sufficient intake air charge.[21]

Evaporative emissions from diesel engines are insignificant due to the low volatility of diesel fuel. Diesel engines can have significant crankcase emissions. Since an engine's piston rings cannot provide a perfect seal with the cylinder walls, a small fraction of the products of combustion leak past the piston rings into the crankcase. This flow of material, known as blowby gases, mixes with the mist of lubricating oil present in the crankcase and must be vented from the crankcase.

3.2 Locomotive Operating Characteristics

Currently, almost all locomotives used in the U.S. are powered by petroleum-fueled diesel engines. As noted in Chapter 2, power produced by the engine is converted to electricity in an alternator and is subsequently used to move the locomotive by means of electric motors at the wheels. This mechanical decoupling of the engine from the drive wheels is significant, in that it allows locomotives to be designed such that their engines operate in generally steady-state mode in several discrete load and speed points. It also allows the engine speed for a given power output to be optimized for fuel economy (and/or emissions) at that power output level. This is in contrast to most other vehicles, in which the engine and drive wheels are mechanically connected through a transmission, allowing highly transient operation. The crankshaft rotational speed of engines (engine speed) used in highway vehicles is related to the speed of the vehicle, while engine power output at any engine speed can vary from zero to the maximum possible at that engine speed.

From the perspective of NOx formation in locomotives at a given power output, it would be desirable to operate the engine at higher rather than lower speed, since higher speeds are associated with lower combustion temperatures. This operational approach is undesirable, however, from the perspective of both fuel efficiency and the formation of PM. As previously described, locomotive engines are designed to operate only at specific power output levels and engine speeds, and these engine operating conditions are decoupled from locomotive speed. With the exception of idle and dynamic brake, locomotive engines used in freight operations tend to be operated at or

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[21] Lizhong, S., et al., "Combustion Process of Diesel Engines at Regions With Different Altitudes," SAE Paper 950857, 1995.

close to the maximum power levels achievable at the corresponding engine speed. This method of operation, while optimizing fuel efficiency and producing relatively low PM emissions, causes high combustion temperatures and corresponding high NOx emissions. Changing the basic operating pattern by operating the engine at higher speeds for given power output levels would tend to reduce combustion temperatures and thereby NOx formation. The consequences of this approach could, however, be a deterioration in fuel efficiency, an increase in PM formation, and the need for larger engines to achieve the same power output, which would tend to further reduce fuel efficiency.

Finally, because locomotive engines are operated at discrete steady-state operational points, the design of low emissions control strategies is expected to be significantly easier than for a engine undergoing more transient operation, such as a highway truck engine. A locomotive engine will only need to be optimized at about ten discrete points for low emissions rather than at an infinite set of conditions over the entire engine torque map. Additionally, at each point the engine operates in an essentially steady-state condition so that changes in speed and load do not have to be considered over the entire engine map. Therefore, calibration of parameters such as aftercooling temperature, fuel injection timing, EGR rate, and others can be better optimized. Furthermore, a less sophisticated electronic control system is required than would be necessary for the same emissions control in highway applications.

3.3 Emission Reduction Technologies

This section provides a summary of emission reduction technologies that EPA considered with respect to their potential applicability to locomotives. The technologies discussed are broken into the following categories; engine technologies, exhaust aftertreatment technologies, and changes in fuel (including the use of alternative fuels) and in lubricating engine oils. Many of these emission reduction technologies are based on industry experience used to reduce emissions from similar but smaller engines,[22] used in highway trucks since the 1970's. While many of the emission-control technologies for highway trucks are conceptually applicable to locomotives and locomotive engines, the design and operation of locomotives and locomotive engines may reduce the effectiveness of some of these technologies in locomotive applications. Among the major differences which may potentially impact the application of these controls to locomotives are the size and design of the engine (for example, a substantial portion of the current locomotive fleet consists of two-stroke engines, whereas most heavy-duty truck engines are four-stroke), the engine operating speeds (locomotive engines tend to have top speeds of just over 1000 rpm, whereas highway engine top speeds tend to be well over 2000 rpm), and size constraints of the vehicle and the infrastructure in which it operates (locomotives

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[22] In many cases the swept volume of a single cylinder of a locomotive engine is as large as the total swept volume of all the cylinders of a highway diesel truck engine.

must often operate in tunnels and on side-by-side tracks). This last difference is important when considering available space for charge air cooling and aftertreatment devices.

It is also important to note that some of the technologies discussed in this section are still in the research and development phase, and may not be available for locomotives for many years, if at all. Section 3.4 summarizes which of these technologies EPA believes will be available in the time frames being considered here. One final note with respect to the technologies discussed in this section is that, while each is discussed in isolation, the effective use of some of these technologies can be optimized through the use of other technologies, and adverse effects of some technologies can be limited or eliminated through the application of other technologies. Thus, many of the technologies presented here are more appropriately viewed as components of larger emission reduction systems or strategies.

3.3.1 Engine Technologies

Fuel Delivery System

Fuel injection improvement is an area that has high potential for emission reductions from locomotive diesel engines. Emissions can be improved by modifying fuel injection pressure, fuel spray pattern, injection rate and timing, and by the use of electronics to control injection rate and timing. While each of these changes, taken separately, can provide emission reductions, these modifications can be used together to optimize individual pollutant reductions and minimize fuel economy penalties. Electronic controls have been instrumental in coordinating these individual modifications for diesel trucks and have played a significant part in allowing diesel truck engines to meet very stringent EPA emission standards for NOx, PM, HC, and smoke, while maintaining fuel economy.

The design of the fuel injector nozzle and the pressure applied to the fuel determines the fuel spray pattern. The spray pattern from the nozzle needs to be optimized in conjunction with the configuration of the combustion chamber and induction swirl to achieve emission reductions. The objectives of this optimization would be to reduce fuel dropout on the surfaces of the combustion chamber, reduce sac volume (the volume at the tip of the injector that retains fuel after the injection) to limit end of injection "dribble", improve fuel atomization and achieve more thorough mixing with the intake air. These potential changes would reduce HC, PM and smoke emissions by promoting full combustion and reduce NOx emissions by reducing local "hot spots" in the combustion chamber.

Modified injection timing is expected to be one of the primary strategies used for meeting the Tier 0 and Tier 1 emission standards, since optimizing injection timing and duration can achieve significant NOx emissions reductions at minimal cost.

Injection timing modifications can reduce NOx emissions by lowering peak combustion pressures and temperatures. Emissions data generated for AAR indicate that retarding fuel injection by 4 degrees from factory specifications reduces NOx emissions by over 30 percent on some locomotives.[23,24] The greatest reductions (31 percent) were seen on a two-stroke cycle switch locomotive. All of the line-haul locomotives tested showed reductions around 25 percent, while the two passenger locomotives tested showed reductions of 13 to 18 percent. However, due to the lower combustion temperatures, an accompanying loss in fuel economy was found. The measured increases in fuel consumption varied from 0.8 to 2.5 percent, with most falling in the 1.0 to 1.3 percent range. EPA expects that some or all of this fuel economy penalty could be made up through the use of other technologies discussed in this chapter. However, given the limited lead time available to comply with the Tier 0 emission standards, it is expected that the primary efforts of the manufacturers and remanufacturers will initially go toward emissions compliance, and that efforts to minimize fuel consumption will only take priority after emissions compliance has been achieved. Thus, it may take a significant amount of time after the effective dates of the standards for the fuel economy penalty to be erased.

In addition to the fuel economy impact just discussed, increased particulate and smoke emissions can result from the use of a significant degree of retarded injection timing, due to the reduced opportunity for the particles to burn. The actual sensitivity depends strongly on the shape of the NOx vs. PM tradeoff curve for each engine configuration. This in turn depends on several design variables which can be modified to minimize the effect. Lower fueling rates is a simple approach to reducing smoke emissions with retarded injection timing, although it would result in reduced power output. Such an approach will likely be used only for those locomotive applications that would not be significantly impacted by a moderate power reduction.

Increasing the overall injection rate can be used to shorten the duration of the fuel injection event. This shortened duration allows a delay in the initiation of fuel injection, similar to the effect of retarded injection timing, causing lower peak combustion temperatures and reduced NOx formation. Increasing the injection rate tends to reduce the PM and fuel economy penalties of retarded injection timing, because the termination of fuel injection is not delayed. However, increased injection rates mean increased injection pressure, and thus increased loading on the components which power the injector. A redesign of these parts to maintain durability would probably be necessary.

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[23] Locomotive Exhaust Emission Field Tests - Phase I, Association of American Railroads Report No. R-877, October 1994.

[24] Locomotive Exhaust Emission Field Tests - Phase II, Association of American Railroads Report No. R-885, March 1995.

Injection rate shaping is a strategy in which the rate of fuel injection is varied in a controlled manner over the duration of the injection period to reduce emission formation. In one approach, a small, early burst of fuel (known as pilot injection) initially enters the combustion chamber, and injection of the majority of the necessary fuel is slightly delayed until the fuel in the combustion chamber ignites. Injection rate shaping can reduce NOx formation, because delaying injection of most of the fuel lowers peak combustion temperatures, thus reducing NOx formation. One study on a heavy-duty diesel truck engine showed a 25 percent reduction in NOx at 1000 rpm by using a pilot injection while still improving fuel consumption and reducing PM and smoke emissions.[25] In another study, a strategy using multiple injections was shown to be capable of offsetting the negative impacts of timing retard on PM emissions by maximizing the burning of PM late in the combustion event, while maintaining flame temperatures low enough to avoid NOx formation.[26]

Increasing injection pressure improves the atomization of the fuel and increases the mixing of the fuel with the intake air in the combustion chamber. This combination of reduced droplet size and improved mixing leads to more complete combustion and decreased formation of PM. Tests on a high-speed diesel engine showed PM emissions to be reduced by half, with NOx held constant through timing retard, when injection pressures were raised from 90 to 160 MPa.[27] One drawback of higher injection pressures is the need to strengthen the fuel-injection system and other components of the engine to deal with higher injection pressures. Without strengthening of components, a loss in durability could result. The ability to increase injection pressure, either on existing engines or on future engines derived from present designs is highly subject to the existing design. On some engines, such as those which use unit injectors, the magnitude of the changes necessary should not be extreme. On other engines, those using separate injection pump, fuel distribution lines and injectors, the necessary redesign would be more substantive.

Another desirable goal for fuel injectors is to limit sac volume. Sac volume is the small volume of fuel remaining in the tip of the injector at the end of injection. This fuel may dribble out of the injector at the end of injection and at low loads, causing increased HC and PM emissions. At high loads this effect is limited during the

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[25] "Reduction of Diesel Engine NOx Using Pilot Injection," T. Minami, et al, SAE 950611, 1995.

[26] "Reducing Particulate and NOx Using Multiple Injections and EGR in a D.I. Diesel," D. Pierpont, et al, SAE 950217, 1995.

[27] "Effects of Injection Pressure and Nozzle Geometry on D.I. Diesel Emissions and Performance," D. Pierpont, R. Reitz, SAE 950604, 1995.

combustion stroke, because the much higher pressures in the combustion chamber tend to hold the fuel in the nozzle. However, during the low-pressure exhaust period the fuel may dribble from the injector and be emitted as HC. Some fuel injection nozzles have been designed to close the injector spray orifices quickly and completely at the end of the injection stroke.

At steady-state, smoke emitted by properly operating diesel locomotive engines is minimal. However, it can occur during periods of engine acceleration, and some engine designs are more prone to generate smoke at this time than others. Most typically, the puff of smoke produced during acceleration is caused by "turbo lag," which is time required for the turbocharger to reach its appropriate operating speed after an increase in exhaust flow occurs. As described below, this results in insufficient air output from the turbocharger for the amount of fuel supplied during accelerations. Due to pressures from public reaction, locomotive manufacturers have been reducing visible smoke from the exhaust of properly operating diesel locomotive engines with a component called a "puff limiter", which limits the rate at which additional fuel is supplied to the engine during accelerations, and thereby compensates for turbo lag. The primary disadvantage of a puff limiter is that it causes slower or delayed acceleration of the engine. This would not be as great a problem for locomotives as for highway trucks, since locomotive operation is less transient. Costs associated with the use of a mechanical puff limiter are relatively low. Electronically controlled puff limiters are more expensive, but should be more effective and less susceptible to tampering than mechanical designs. As an option, a turbocharger capable of increased air flows can be used to ensure that enough air is available to avoid reaching the smoke limit during accelerations. If such a turbocharger were used, a wastegate could be used during steady-state operation to prevent overcharging of the cylinder. The wastegate would essentially route some of the exhaust away from the turbine.

Charge Air Compression and Cooling

The typical goal in engine design is to achieve the desired power output and reliability, while constraining weight and size, at the lowest possible cost. A common method to achieve an increase in power output without an increase in engine size (displacement) and weight, is the use of charge air compression (e.g., turbocharging). A turbocharger uses the energy of the hot exhaust gases to turn a turbine, which in turn is attached to an air compressor in the intake air stream. This approach increases the mass of air entering the engine's combustion chambers, which allows more fuel to be used, which increases power output. However, charge air compression also heats the intake air, which increases the formation of NOx. Durability also becomes a significant concern due to elevated temperatures and loads. These problems can be resolved through the use of charge air aftercooling, which will be discussed shortly.

Charge air compression can be accomplished in various ways, but the dominant method used for diesel engines is turbocharging. The charge air compression process must be closely linked to the engine fuel control system to ensure that the two work together properly, thus ensuring that fuel consumption and emissions formation are minimized, including preventing smoke generation due to turbo lag. The magnitude of this problem varies between engines produced by different locomotive manufacturers. As noted above, one method commonly used to address this problem is to slowly increase the fueling rate following a change in throttle position. Other methods to address this problem include the use of a variable geometry turbocharger (VGT), multiple turbochargers, electronic matching of the turbocharger and fuel injection, or mechanical drive of the compressor (*i.e.*, the use of a supercharger rather than a turbocharger). A variable geometry turbocharger can significantly reduce the problems of turbocharger lag. By changing the geometry of the gas flow passages in the turbine, the response time of the turbocharger can be improved. For instance, one design uses a sliding mechanism to block part of the exhaust flow passage in the turbine. Because the same amount of exhaust has to pass through a smaller flow passage, the exhaust gasses must travel faster which, in turn, causes the turbine to spin faster. VGTs require slightly more space, are more costly than a conventional turbocharger. Over a section of the on-highway transient Federal Test Procedure, particulate reductions of up to 34 percent have been achieved on a heavy-duty diesel truck engine through the use of a VGT, without increasing NOx emissions.[28]

The heating that is caused by compression of the charge air increases NOx emissions. This can be minimized by cooling the charge air after compression. Charge air cooling also increases the mass of air available for combustion, and may reduce durability problems associated with high combustion temperatures. While the lower temperatures can cause some increase in PM emissions, if the decrease in combustion temperatures is small enough, PM emissions may be unaffected or may even decrease (due to the additional oxygen available for combustion). One study showed that charge air cooling resulted in decreased smoke, HC, NOx, and PM emissions and fuel consumption, especially at high loads where most NOx is created.[29]

There are two basic types of charge air coolers (or aftercoolers): air-to-liquid units and air-to-air units. Historically, in air-to-liquid systems, engine coolant has been used as the cooling medium both for highway trucks and locomotives. The amount of cooling with an engine coolant system is limited by the relatively high temperature of the coolant. Air-to-air aftercoolers use a stream of outside air flowing through the device to cool the charge air. By using ambient air, an air-to-air

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[28] "Optimization of Heavy-Duty Diesel Engine Transient Emissions by Advanced Control of a Variable Geometry Turbocharger," A. Pilley, et al, SAE 890395, 1989.

[29] "Performance and Emissions Trade-Offs for a HSDI Diesel Engine - An Optimization Study," Z. Bazari, B. French, SAE 930592, 1993.

aftercooler can cool the compressed intake air to a temperature approaching that of the ambient air, and thus can be more effective in lowering the temperature of the compressed charge air and thus reducing NOx levels.

Air-to-air aftercoolers are widely used at present in diesel engines for highway truck operations, and the potential exists for their use on locomotives as well. However, air-to-air aftercoolers generally rely heavily on ram air[30] to get cooling air into the aftercooler system. While this is not a problem for trucks operating at highway speeds and which have the engine, the aftercooler and the engine radiator mounted in the front of the vehicle, it could be more problematic for locomotives. For multi-locomotive trains, there exists no comparable direct frontal area for introduction of ram air into the aftercooler systems of locomotive engines. Air scoops or air dams could be used to divert air into an aftercooler system. Any air scoops or air dams installed on a locomotive would need to be bidirectional, facing the "front" and the "rear" of the locomotive. This is because locomotives can and do operate in both directions. The size and shape of any air scoop system is also limited by the space constraints on the locomotive itself, and space constraints due to the infrastructure in which the locomotive must operate. In addition, locomotives often operate at maximum engine power and low locomotive speed for extended periods of time, which means that little air would be introduced to an air-to-air aftercooler system due to ram air. Blower fans could be incorporated to insure that a sufficient quantity of air is introduced into the aftercooler system. It is possible that the cooling fans already used on locomotives for engine cooling or the fans used to dissipate the heat generated during dynamic brake could be made to serve a dual purpose.

Air-to-liquid aftercoolers (e.g., radiators) are the type currently in general use for locomotive applications, in one of two configurations. As previously noted, one type uses engine coolant to lower engine intake air temperature to a level near the operating temperature of the engine coolant. This limits the amount of cooling that can be accomplished due to relatively high engine coolant temperatures. However, as a result, the temperature of the engine intake air, and thus the level of emission control, is somewhat self-regulating and remains relatively constant (near the engine coolant temperature) over a wide range of ambient temperatures. The overall effectiveness of this approach might be improved by increasing the overall size of the heat exchanger area, the air-to-surface ratio in the system, or by using a cooling fluid with a higher heat capacity.

The second type of air-to-liquid charge air cooling system is an aftercooler using a coolant system separate from the engine coolant system. Such a system, also known as split cooling, has been used on some recent production locomotives. Split cooling can cool engine intake air temperatures almost as effectively as an air-to-air aftercooler.

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[30] The term ram air is used to denote the air forced through an aftercooler and/or a radiator by the motion of the vehicle.

However, coolant temperatures are tied to ambient temperatures, necessitating appropriate controls to reduce seasonal variations in intake air temperature. The use of antifreeze would probably be necessary to prevent freezing of the aftercooler system under low ambient conditions (which represents a departure from current railroad practice of not using antifreeze). Introducing a separate liquid system for aftercooling could also be more complex than either of the other above-mentioned systems. Space constraints on a locomotive would also need to be considered.

A third type of potential air-to-liquid system is a combination of the two previous types with charge air being routed only through the separate coolant system components during high ambient temperature operations, and through both the separate coolant and engine coolant system components during low ambient temperatures to prevent overcooling. This more complex approach to control of overcooling, while theoretically possible, is expected to be a more costly approach than could be achieved by other means.

Combustion Chamber Modifications

Diesel truck engine manufacturers have achieved significant emission reductions through changes to the engine's combustion chamber. Combustion chamber design modifications can also reasonably be expected to provide emission reductions for locomotive engines. Redesign of the shape of the combustion chamber and the location of the fuel injector can optimize the motion of the air and the injected fuel with respect to emission control. Reductions in both NOx and PM are expected to be achieved with some combustion chamber configurations currently under development.

Compression ratio is another engine design parameter that impacts emission control. In general, lower compression ratios cause a reduction in NOx emissions and decreased fuel economy, but also cause an increase in PM emissions, while higher compression ratios tend to have the opposite effects. Lower compression ratios also play a part in lowering the loads imposed on the components of the engine and, as a result, may contribute to the durability of the units. Compression ratios employed in locomotive engines are typically somewhat lower than those used in truck engines, although some recent designs have gone to higher compression ratios, possibly for lower PM emissions, but more likely for fuel economy reasons.

Increasing turbulence in the combustion chamber either as a result of turbulence in the intake air, by chamber design, or a combination of both (*i.e.*, inducing "swirl") can reduce PM emissions from diesel engines by improving the mixing of air and fuel in the combustion chamber. Historically, swirl has been induced in truck engines by intake air routing and by chamber design. Truck manufacturers are, however, increasingly using "reentrant" piston designs, in which a lip is formed at the top of the piston bowl into which the air is compressed, thereby causing controlled swirl. Manufacturers are investigating the applicability of this chamber design to locomotive engines. A change in materials or a change in the shape of the chamber may be helpful in adapting this strategy to locomotive use, and the technology holds promise for application on locomotives.

Combustion chamber design can be further optimized to decrease PM emissions. The location of the top piston ring relative to the top of the piston has undergone significant investigation in truck engines. The location of piston rings has been modified to reduce the crevice volume, i.e, the space between the top ring and the top of the piston, while retaining the durability and structural integrity of the piston and piston ring assembly. These changes result in reduced HC and PM emissions. Raising the top piston ring requires modified routing of the engine coolant around the cylinder to prevent overheating of the raised ring. Applicability of this approach to locomotive engines is under investigation.

Some designers are investigating the possibility of adding ceramic materials to the surfaces of the combustion chamber. Ceramic coatings may provide effective insulation, allowing more energy to be retained in the products of combustion and thereby increasing fuel efficiency. Retaining more energy in the combustion chamber increases peak combustion temperatures, resulting in decreased PM emissions and increased NOx emissions. When combined with other modifications such as modified injection timing, rate shaping and reduced fueling rate, the use of ceramics may result in a reduction in PM without a corresponding increase in NOx emissions or fuel consumption.

Electronic Controls

Various electronic control systems have been developed and are already in use on some newer locomotives. EPA expects that the electronic control systems currently in use will continue to be improved. Use of electronic controls enables designers to implement much more precise control of the fuel injection system, such as injection rate shaping and variable injection timing, than is possible with a mechanical system. This allows designers to achieve improved emission control with little or no fuel consumption penalty. The contractor cost report estimates that electronic controls would result in a two percent fuel consumption savings in locomotives, which could offset the fuel consumption penalty associated with retarded injection timing.[31] Also, electronic controls are necessary for implementation of advanced concepts such as rate shaping.

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[31] "Cost Estimates for Meeting the Proposed Locomotive Emission Standards," Engine, Fuel, and Emissions Engineering, Inc., September, 1997

Reduced Oil Consumption

Manufacturers have evaluated, and continue to evaluate means for reducing the consumption of lubricating ("lube") oil, which would result in a lower lube oil contribution to PM emissions. The trade-off which is made in reducing oil consumption is with engine durability. Since durability is a very high priority in locomotive engines, EPA expects that manufacturers will continue to strive to reduce oil consumption, but not at the expense of durability. Any significant benefits in PM control which may be attributable to reduced oil consumption will probably be more of a longer-term undertaking. This effort may also lead to the eventual disappearance of two-stroke cycle engines from locomotive use, since four-stroke engines generally are able to achieve better oil control, resulting in much less oil as a PM constituent.

Intake Air Dilution

Displacing some of an engine's intake air with inert materials is another NOx reduction strategy. The inert material lowers combustion temperatures by diluting the mixture in the cylinder and absorbing heat from the burning fuel. The reduced temperatures caused by intake air dilution, with or without aftercooling of the intake air, result in lower levels of NOx emissions. Two identifiable methods are exhaust gas recirculation (EGR) and water injection.

Exhaust gas recirculation uses gases from the exhaust stream to dilute the combustion mixture. The recirculated exhaust gases absorb a portion of the energy released during combustion of the fuel, decreasing the peak combustion temperature and reducing NOx formation and engine power. EGR in gasoline-fueled engines is most often accomplished by routing a portion of the exhaust stream from the exhaust system into the intake air. As an alternative, manufacturers may use "internal" EGR by coordinating the timing of the intake and exhaust valve events so that a portion of the exhaust gas from the previous combustion event is retained in, or drawn back into, the combustion chamber. This approach is less costly in terms of hardware requirements, but also less effective than external EGR. One study on a single cylinder engine showed that when combined with turbocharging and charge air cooling, 20 percent EGR can reduce NOx by approximately 50 percent without penalties in smoke or HC emissions.[32]

While EGR has been successfully applied in gasoline engines, there are some potential drawbacks in the application of EGR to the diesel engines used in locomotives. The abrasiveness of the particulate matter in the exhaust stream may cause accelerated wear in the engine and turbocharger, and PM can also find its way into the engine lubricating oil. Also, the particulate matter can form deposits on

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[32] "Combined Effects of EGR and Supercharging on Diesel Combustion and Emissions," N. Uchida, et al, SAE 930601, 1993.

components of the engine intake system, decreasing the heat transfer capability of the aftercooler, and potentially decreasing the effectiveness of the turbocharger if introduced upstream of this unit. In addition, by reducing combustion temperatures and decreasing the amount of air available for combustion, EGR may cause incomplete combustion, resulting in increased HC, CO, PM and smoke emissions.

There are several methods of controlling the PM emissions attributed to EGR. One method is to cool the exhaust gas recirculated to the intake manifold. With EGR cooling, a much higher amount of exhaust gas can be added to the intake charge. A small NOx penalty due to increased ignition delay was observed on a truck engine at light loads, but at high loads, some additional NOx reduction resulted from EGR cooling.[33] Another method to offset the negative impacts of EGR on PM is through the use of higher intake air boost pressures. By turbocharging the intake air, exhaust gas can be added to the charge without reducing the supply of fresh air into the cylinder.[34] Because locomotive engines generally operate at a discrete number of steady-state conditions in use, it should be much simpler to optimize the use of EGR than for a highway application which is typically characterized by highly transient operation. Particularly through the use of electronics, EGR rates can be optimized with the air and fueling strategy independently for each notch. Concerns associated with transient operation, such as those related to the problem excess EGR during decelerations, are minimal.

One study considered a technology package designed to solve the problems of minimizing the amount of intake charge displaced by exhaust gas and of fouling the turbocharger and intercooler.[35] This technology package uses a variable geometry turbocharger (VGT), an EGR control valve, and a venturi mixer to introduce the recirculated gas into the inlet stream after the intake air is compressed and cooled. In addition to compressing the intake air, the VGT is used to build up pressure in the exhaust stream. Once the pressure is high enough, the EGR control valve is opened and the recirculated gas is mixed in to the high pressure inlet stream. Although the recirculated gas is cooled, this cooling is kept minimal to prevent both fouling in the cooler (due to condensation) and a large pressure drop across the cooler.

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[33] "NOx Reduction Strategies for DI Diesel Engines," Herzog, P., et al, SAE 920470, 1992.

[34] "Combined Effects of EGR and Supercharging on Diesel Combustion and Emissions," Uchida, N., et al, SAE 930601, 1993.

[35] "New EGR Technology Retains HD Diesel Economy with 21st Century Emissions," Baert, R., et al, SAE 960848, 1996.

Several bypass oil filtration designs exist for diesel truck engines which will filter the smaller particles (those missed by the primary filtration system) out of engine oil.[36] With bypass filtration, a portion of the oil is run through a secondary unit which results in better filtration of the oil. This type of filtration system could be used to minimize negative effects of PM in the oil that is associated with high levels of EGR. At least one of design claims efficiencies of up to 99% in capturing 1-micron particles. Another design is capable of removing water, as well as particles less than 1 micron in size. To accelerate vaporization of impurities and to maintain oil viscosity, a heated diffuser plate is used in a third design. A low-voltage soot removal device that reduces the PM in the recirculated gas by 50 to 84 percent has been developed. Engine wear was shown to be greatly reduced on a test truck engine as a result of this device. Testing was performed at 30 percent EGR.[37] Another strategy for reducing particles in EGR is to recirculate the exhaust gas after it has passed through a particulate trap. Traps typically can remove more than 90 percent of particulate matter, whereas some designs have achieved a 99 percent particle collection efficiency.[38,39]

A hybrid EGR system is also being studied as a potential solution to durability problems associated with recirculated diesel exhaust.[40] In this system, a small gasoline engine is used to drive the supercharger for a larger diesel engine. A portion or all of the gasoline engine exhaust can then be fed into the intake stream of the diesel engine. Because of the lack of sulfuric acid and the very low carbon content in the gasoline filtration, a portion of the oil is run through a secondary unit, engine exhaust, the problems of wear and erosion of parts in the diesel engine associated with EGR are alleviated. Another bonus of this system is that the boost pressure is independent of the load and speed of the diesel engine. Therefore, there is more flexibility in optimizing the emissions and fuel consumption of the diesel engine. The study referenced above showed that the hybrid EGR system had about the same fuel consumption as a conventional EGR engine, but with a larger NOx decrease. However, such systems are far from being ready for practical use.

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[36] *Fleet Owner*, “Hardware Report: What’s new in... Bypass Filtration,” magazine article, January 1997.

[37] "The EGR System for Diesel Engine Using a Low Voltage Soot Removal Device," Yoshikawa, H., et al, SAE 930369, 1993.

[38] "Reducing Diesel Particulate and NOx Emissions via Filtration and Particle-Free Exhaust Gas Recirculation," Khalil, N., et al, SAE 950736, 1995.

[39] "An Optimization Study on the Control of NOx and Particulate Emissions from Diesel Engines," Larsen, C., et al, SAE 960473, 1996.

[40] "An Elegant Solution for Vehicular Diesel's Emission and Economy - Hybrid EGR System," Akiyama, M., et al, SAE 960842, 1996.

Water injection is a second form of intake air dilution. Water injection works like EGR, absorbing heat to vaporize the water and heat the resulting steam, which lowers peak combustion temperatures and decreases NOx formation. Since the water would be introduced as a liquid, only a very small portion of the charge air volume would be displaced, and the effects on engine power would not be large. Testing on a diesel engine has shown a 40 percent reduction in NOx with a water-fuel ratio of 0.5 with only a slight increase in smoke emissions.[41] However, water injection imposes significant technical and regulatory problems. First, it can lead to increases in PM and smoke emissions. Second, the water can cause corrosion of engine components, and the use of water with dissolved impurities (such as calcium carbonate) could lead to deposits in the water injection system and in the engine. Purified water would be needed to avoid such deposits. Also, insulation in the water tank and injection system or additives to the water would be necessary to prevent the water from freezing in winter. Finally, water injection would require the engine operator to refill the water reservoir periodically.

Emission control systems that require an operator to physically perform alterations or additions to a system may not be effective in the field in achieving emission benefits, especially if not performing those acts would not seriously decrease engine performance. Because the engine could potentially function without the water as well as it would with it, there may be no incentive for the operator to comply with the requirement. Because of the large amounts of water that would be needed, water injection for a locomotive application could possibly require the addition of a "water car" behind the locomotive, adding additional weight to the train. Additionally, railroad companies may have to develop infrastructure in the form of purified water storage tanks in train yards and along track, similar in concept to the water towers used for old steam powered locomotives.

Turbo-Compounding

Turbo-compounding is the addition of a second power recovery turbine in series with the turbine of the turbocharger. This second turbine captures and converts some of the remaining energy in the exhaust gases to useful work. This useful work is transmitted to the crankshaft by a gear train, thereby increasing overall engine efficiency. By reducing fuel consumption, addition of such a waste heat turbine would lead to a corresponding reduction in overall exhaust emissions on a g/bhp-hr basis. A waste heat turbine may require the application of ceramic engine designs. The durability of such systems has yet to be addressed for locomotive applications, although they were successfully used in piston-driven aircraft applications for a number of years.

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[41] "Reduction of Smoke and NOx by Strong Turbulence Generated During the Combustion Process in D.I. Diesel Engines," SAE 920467, 1992.

Also, the addition of the extra turbine could pose packaging problems for current locomotives. Costs associated with this approach are expected to be high for the amount of emission reductions achieved. If utilized, EPA expects that it would only occur in the long term.

Closed Crankcase

Preventing the discharge to the atmosphere of the mixture of blowby gases and lubricating oil mist in the crankcase is referred to as "closing the crankcase" and in the case of gasoline-fueled engines has been achieved by routing the blowby gases to the engine air intake. EPA regulations applicable to highway diesel engines require the use of closed crankcase systems only on naturally aspirated diesel-fueled engines. EPA exempted diesel-fueled truck engines with charge air compression because of the possibility of blowby gases decreasing the effectiveness of turbochargers and aftercoolers. For highway diesel engines equipped with charge air compression, closing the crankcase would depend on the development of designs that protect turbochargers and aftercoolers from damage. On some turbocharged locomotive engines, crankcase closure is effectively achieved by routing the blowby gases into the exhaust stream after the turbocharger. Since exhaust HC emission measurements for such systems include HC emissions in the blowby gases, this approach can be considered as meeting the intent of a closed crankcase. There appear to be no negative effects on fuel efficiency or engine performance.

3.3.2 Exhaust Aftertreatment Technologies

In order to meet EPA's NOx and PM standards for on-highway heavy-duty diesel engines, manufacturers have investigated exhaust aftertreatment as a supplement to engine-based emission control technologies. This technology is theoretically transferrable to diesel engines used in locomotives, giving consideration to space availability on the locomotive and the durability of the technology. In general, incorporating exhaust aftertreatment is more expensive than modifying engine designs, but aftertreatment can result in additional emission reductions beyond those achievable through changes in engine design. Aftertreatment may also lessen the trade-offs involved in controlling both NOx and PM emissions while retaining fuel efficiency. For example, the use of aftertreatment devices to control PM emissions would provide engine designers more flexibility to focus on reducing NOx formation in the engine. In general, development efforts for aftertreatment devices for locomotive applications are behind those efforts associated with improving engine-out performance.

Work is being done to develop reduction catalysts that would specifically reduce NOx emissions. These devices, known as selective catalytic reduction (SCR) systems require an adequate concentration of substances called reductants or reducing agents that react readily with NOx. Reduction catalyst technology is currently in the development stage for mobile diesel applications, although such catalysts have been used successfully in industrial applications. The goal of these catalysts is to lower NOx emissions in the presence of the oxygen-rich exhaust gases characteristic of diesel engines. These types of catalysts are therefore sometimes called lean-NOx catalysts.

While finding space on the locomotive to install an aftertreatment device is a concern, the primary challenge in the use of catalyst technology to control NOx from locomotive diesel engines is the need to provide adequate supply of a reducing agent in the exhaust stream. Two means of achieving this are the supplemental injection of reducing agents and a diesel exhaust-NOx catalyst which utilizes the exhaust hydrocarbons already present as a reducing agent. Both types of catalyst systems typically make use of zeolite molecular sieves, selectively trapping the molecules of reactant materials. Zeolite sieves are substances with a crystalline structure capable of trapping molecules of certain sizes while allowing others to pass through.

The reducing agents most typically considered for injection into the exhaust stream are urea, ammonia and diesel fuel. Urea and ammonia are effective reducing agents in industrial applications, achieving high NOx reduction efficiencies in steady-state operation.[42] Developing such catalysts for highway diesel applications has been difficult due to the transient operating characteristics of highway vehicles, which require these systems to be effective under frequently varying load conditions. This would be less of a consideration in designing for locomotive operation, which is more like a series of steady-state modes. One SCR supplier has claimed that recent advances in the predictive modeling of emissions at various operating modes and the development of corresponding reductant metering strategies has resulted in NOx reductions of 90%, with concurrent PM reductions of 50% and HC reductions of 85%.[43]

Relying on urea or ammonia for effective catalyst operation also raises regulatory concerns. These chemicals are consumed to achieve NOx reduction, so vehicle operators would need to maintain an adequate supply on their vehicles. Operators may have no practical incentive for maintaining an adequate supply of the required reducing agents unless the control systems were designed such that running out of the reducing agent would cause vehicle performance to be seriously degraded. Without such a safeguard there would be little incentive to keep an adequate supply of reducing agent in a locomotive, since the lack of reductant would otherwise be transparent to the operator. One must not only consider the initial cost of the hardware and the ongoing cost of the reducing agent, but also the cost of the reducing agent refilling infrastructure that must be developed to support locomotives utilizing such technology.

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[42] "Catalytic NOx Reduction in Net Oxidizing Exhaust Gas," W. Held, SAE 900496, 1990.

[43] Docket items A-94-31-IV-D-8 and A-94-31-IV-E-3.

The use of ammonia and urea as reductants on locomotives poses another potential problem because exhaust gas temperatures from locomotive engines in most throttle notches may be lower than the minimum required for proper operation of the catalyst. Usage could be limited to high loads where NOx is formed, or another suggested approach to solving this problem involves the injection of additional diesel fuel into the exhaust gases for combustion, thereby increasing exhaust gas temperatures to levels sufficient for the reduction reactions to occur. In such a design, a small amount of diesel fuel is sprayed into the exhaust stream upstream of the catalytic converter in metered amounts, corresponding to engine NOx output levels. NOx reduction efficiencies of 30 to 80 percent have been reported in steady-state experimental systems.[44,45] The reported NOx reduction efficiency of 80 percent corresponded with a 5 percent loss in fuel economy. Fuel used for this purpose would obviously have negative effects on fuel efficiency, increasing operating costs and possibly raising HC, CO, PM and smoke emissions. (Fuel efficiency decreases, because fuel that is injected for NOx reduction does not produce power output from the engine.) Using unburned diesel fuel as the injected reducing agent would, however, tend to resolve the concern over operator participation because the fuel would always be available on a locomotive.

Chemical aftertreatment with cyanuric acid is also being investigated as a method to reduce NOx emissions. As exhaust gas passes over cyanuric acid pellets, the pellets give off cyanic acid gas (HCNO), which reacts with NOx to form nitrogen, carbon dioxide and water. California has identified this as a "best available technology" for stationary sources which have largely steady-state operation with relatively gradual changes in output power levels. This type of operation is similar in some ways to that for locomotive engines.

Aftertreatment devices such as oxidation catalysts may be considered for use on locomotives to reduce PM emissions. PM emissions from diesel engines are composed of carbonaceous particles, a soluble organic fraction, sulfates and adsorbed water. Oxidation catalysts tend to reduce the soluble organic fraction and have little effect on the carbonaceous portion of PM in diesel exhaust, since soluble organic fractions arise from unburned fuel and lubricating oil. This limits the reduction in PM emissions that an oxidation catalyst can achieve. Furthermore, oxidation catalysts convert a portion of the sulfur dioxide present in the exhaust stream to sulfate PM. Because the increased sulfate PM can offset the reduction in the soluble organic fraction, an oxidation catalyst may not be as effective as expected in reducing total PM emissions,

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[44] "Catalytic Reduction of NOx and Diesel Exhaust," S. Sumiya, et al, SAE 920853, 1992.

[45] "Catalytic Reduction of NOx in Actual Diesel Engine Exhaust," M. Konno, et al, SAE 920091, 1992.

especially when high sulfur fuel is used. A major goal in the development of oxidation catalysts for diesel engines is therefore to increase oxidation of the soluble organic fraction while having little if any effect on the oxides of sulfur present. Optimized designs (addressing operating temperature, exhaust gas flow path, selection of catalyst materials, and other parameters) appear capable of reducing total PM emissions from diesel engines using low sulfur fuel by 20 to 30 percent.[46,47]. Actual reductions are very dependent on the magnitude of the soluble organic fraction (compared to the carbonaceous portion) from engine-out exhaust. The mandatory use of low sulfur diesel fuel in locomotives would have to be considered if catalyst use became widespread.

The durability of diesel engine catalytic converters is unproven for large diesel engines such as are used to power locomotives. However, experience gained from light and medium heavy-duty truck and urban bus applications supports the expectation that oxidation catalysts with sufficient durability can eventually be developed for larger, more durable engines used in locomotives.

Another type of aftertreatment is the particulate trap oxidizer (trap) which filters particulate matter from the exhaust stream with subsequent oxidation of the filtered particulate. The basic element of a trap system is a structural shell containing the filter material. Filters currently under development for truck and bus engines are either ceramic wall-flow monolith filters or filter tubes covered with multiple layers of a yarn-like ceramic material. The filter material contains many small holes that allow the exhaust gases to pass through while collecting the particulate from the raw exhaust.

The particulate matter collected by the filter eventually needs to be removed. It is generally burned off in a process called regeneration. Two general approaches for regeneration of the trap have been investigated. One approach employed is the use of catalytic material on the filter which causes regeneration once a predetermined trap loading is reached. The other approach includes a system for heating the filter to oxidize the particulate, a microprocessor for controlling filter regeneration and, in some systems, a supplemental air supply system.

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[46] "Effects of Sulfate Adsorption on Performance of Diesel Oxidation Catalysts," N. Harayama, et al, SAE 920852, 1992.

[47] "Technical Feasibility of Reducing NO_x and Particulate Emissions From Heavy-Duty Engines," Acurex Environmental Corporation, April 30, 1993, p. 3-38.

3.3.3 Changes in Fuel and Lubricating Oil

Diesel fuel

There are some changes that could be made to the composition of diesel fuel to reduce emissions, at the expense of requiring the railroads to use new and more costly fuels. Also, the possible changes to diesel fuel tend to be interdependent. For example, an increase in a fuel's cetane number is usually associated with a decrease in aromatic content and an increase in volatility. It is therefore difficult in some cases to determine separately the effects of changing individual parameters.

The cetane rating is a measure of the tendency of a fuel to autoignite. The effect of raising the cetane rating of diesel fuel is that it increases autoignition of the fuel in the combustion chamber, generally improving combustion. A fuel's cetane rating can be increased either with a fuel additive that enhances autoignition, or through modified processing of diesel fuel at the refinery. Currently, the nationwide average cetane number is approximately 44 for highway diesel fuels[48]. A typical gallon of diesel fuel also consists of 20 to 45 percent aromatic hydrocarbons by volume. Decreasing the aromatic content of diesel fuel, which is closely correlated with increased cetane rating, seems to have a greater potential for decreasing both PM and NOx emissions than changing fuel composition in other ways. In one study reducing the aromatic content of diesel fuel used in truck engines from 40 to 20 percent , and increasing the cetane number from 44 to 53 resulted in a 4 percent reduction in NOx and a 7 percent reduction in PM[49]. In another study, a 10 percent reduction in PM emissions was reported as a result of reducing the aromatic content from 40 to 10 percent.[50]

Sulfur occurs naturally in crude oil and, unless removed, also occurs in refined diesel fuel. Two basic emission problems are associated with sulfur in diesel fuel. First, the sulfur in the fuel reacts to form oxides of sulfur (SOx), including about 3 percent of the fuel sulfur that is directly emitted as particulate in the form of sulfuric acid.[51] SOx can also react in the atmosphere to form sulfate PM. Second, for vehicles equipped with particulate traps or catalysts, fuel sulfur can cause deterioration in the substrate materials, decreasing the effectiveness and durability of the trap or catalyst.

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[48] "National Fuel Survey, Diesel Fuel, Summer 1992," and "National Fuel Survey, Diesel Fuel, Winter 1992," Motor Vehicle Manufacturers Association, 1992.

[49] "Diesel Fuel Property Effects on Exhaust Emissions from a Heavy-Duty Diesel Engine That Meets 1994 Emission Requirements", McCarthy, et al, SAE 922267, 1992.

[50] "Effects of Fuel Aromatics, Cetane Number and Cetane Improver on Emissions from a 1991 Prototype Heavy-Duty Diesel Engine," T.L. Ullman, et al, SAE 902171, 1990.

[51] "Cost-Effectiveness of Diesel Fuel Modifications for Particulate Control," M.C. Ingham and R.B. Warden, Chevron, SAE 870556, 1987.

Modifying diesel fuel to increase its volatility (*i.e.*, tendency to evaporate) would decrease the time required for each fuel droplet to evaporate in the combustion chamber. More rapid and complete evaporation would result in more complete combustion of the fuel and thus reduced PM emissions. However, the resultant increased combustion pressures would probably require stronger engine components to maintain durability at current levels. The effect of increased volatility on NOx is also not well understood. It should be noted that the small increases in the volatility of the diesel fuel referred to here would not lead to significant evaporative emissions.

Derivatives of vegetable oils or animal fats can be mixed with diesel fuel for combustion in a diesel engine. Such fuel mixtures, known as biodiesel, have received attention in Europe as a potential source of renewable fuel. Also, Congress identified biodiesel as an alternative fuel in the National Energy Policy Act of 1992. The biodiesel fuel mixture includes oxygen and, as with oxygenate additives, would likely lead to a decrease in PM emissions while risking an increase in NOx emissions. The costs and emission-reducing potential of these changes are not well understood or quantified at the present time.

Additional modifications to diesel fuel can also reduce diesel exhaust emissions. First, increasing the kinematic viscosity of diesel fuel has been correlated with reduced PM emissions.[52] Second, addition of detergents or other chemicals may reduce the formation of deposits that impair precise control of fuel flow and can lead to increased emissions.

Alternative Fuels

The use of fuels other than diesel fuel has received much interest in the context of on-highway vehicles. The alternative fuels that have received the most attention are natural gas (stored in both compressed gas and liquefied states), alcohols (methanol and ethanol), and liquefied petroleum gas. Currently, only natural gas has received any serious consideration as a potential fuel for locomotives. Thus, although other fuels could someday be available for use in locomotives, this discussion is limited to natural gas.

Natural gas is made up primarily of methane, but also tends to contain some ethane, propane, butane and trace amounts of inert ingredients. It is a gas at standard conditions, which requires that storage onboard a vehicle be approached differently for natural gas than for liquid fuels. The current approach most utilized for on-highway vehicles is to store it as a compressed gas in high pressure cylinders. However, the high fuel usage rate of locomotives is problematic, due to compressed natural gas' extremely low energy density (i.e., amount of energy per unit volume of fuel), and thus

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[52] "Description of Diesel Emissions by Individual Fuel Properties," Noboru Miyamoto, Hokkaido University, et al, SAE 922221, 1992.

the space needed to store sufficient fuel. The second approach to storing natural gas is to liquefy it and store it cryogenically in insulated containers. While much more practical for locomotives, even this approach results in a much lower energy density than diesel fuel, and a separate tender car for the fuel would be required for a liquefied natural gas-powered locomotive which is traveling any great distance.

In contrast to diesel fuel's ability to self-ignite in a compression ignition engine, natural gas has a very high resistance to autoignition. In order to use natural gas in a locomotive engine an ignition source must be provided. The two general approaches to providing the required ignition source are diesel fuel pilot injection and spark ignition.

The GasRail USA late-cycle, high-injection-pressure project is an example of the former approach, and has shown NOx emission reductions of up to 75 percent with no increases in HC and CO emissions.[53] Under the pilot injection approach, a premixed charge of natural gas and air is introduced into the combustion chamber. A small amount of diesel fuel is then injected into the combustion chamber. The diesel fuel autoignites, which in turn ignites the natural gas. Diesel fuel pilot injection systems can be designed to use different ratios of natural gas to diesel fuel, but are generally designed to maximize the use of natural gas. As a result, such systems typically use natural gas for well over 90 percent of the energy needs of the locomotive. However, they usually operate on pure diesel fuel at idle and low load operating points where fuel consumption is low.

The second approach to igniting natural gas is to use a spark ignition system similar to that used on gasoline engines. Since the spark ignition approach is a dedicated natural gas system, it has the advantage of allowing an engine to be optimized for natural gas. However, it is a much more significant departure from a standard diesel engine than the pilot injection system. The pilot injection system is essentially the addition of a natural gas fueling system to a diesel engine. As such, the pilot injection system is much more suited to the retrofit of existing diesels than is the spark ignition system.

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[53] Alternative Fuels Today, July 15, 1997.

Data show that natural gas strategies can be used to achieve significant reductions in NOx and PM. Over the line-haul duty cycle, a dual-fuel locomotive engine achieved NOx and PM levels of 4.2 and 0.33 g/bhp respectively.[54] A dedicated spark-ignition natural gas-fueled locomotive engine was shown to be capable of levels as low as 2.0 g/bhp-hr NOx and 0.09 g/bhp-hr PM over a three mode cycle.[55] However, the HC and CO emissions did not meet the Tier 2 levels for either of these engines. The long term durability of natural gas engines in locomotive use remains unknown. Also, the use of natural gas would require that new refueling facilities be installed at any rail yard which services natural gas-fueled locomotives. One potential area of application would therefore be in switching and terminal operations.

Lubricants

Reductions in PM emissions can be obtained both by changes in the composition of lubricating oil and by a reduction of the oil consumption rate. Refiners are conducting research to formulate such lubricating oils that form less PM for truck engines. Some of this research may or may not be applicable to locomotive engines, since the additives used in lubricants for locomotive engines are different than those used in truck engines. One possibility is to replace the metal additives commonly used in lubricating oil with nonmetallic compounds in order to reduce the noncombustible (ash) portion of the oil.

The use of synthetic oils or partial synthetic oils may reduce formation of PM emissions. Conventional lubricating oil formulations evaporate over a wide range of temperatures. The portion that evaporates at lower temperatures may diffuse into the combustion chamber, increasing PM emissions. Synthetic oils can be formulated to evaporate over a narrow, high-temperature range. Using such synthetic oils would reduce the oil contribution to PM emissions. Partial synthetic oils, made by displacing most of the more volatile portion of a conventional oil with synthetic material, may yield equivalent results. Evaporated oil components would also be present to some extent in the blowby gases introduced into the locomotive exhaust. Since HC exhaust emissions from locomotive engines are already very low, and the measured values may also include blowby gases, EPA does not believe that contributions from present oil formulations to HC exhaust emissions are a problem.

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[54] Fritz, S., "Exhaust Emissions from a Dual Fuel-Locomotive; Final Report," Southwest Research Institute, March 1992.

[55] Comments from W.C. Passie at Caterpillar to Docket A-94-31, "Emission Standards for Locomotives and Locomotive Engines," June 10, 1997.

3.4 Expected Availability of Technologies

The preceding sections were intended to provide a brief overview of the possible technologies that manufacturers of locomotives and locomotive engines could employ in complying with the requirements of this rulemaking. It should be emphasized, however, that these are not mandated technologies and that manufacturers and remanufacturers will develop their own optimized emission control strategies. EPA has also determined that many of the technologies summarized above are not likely to be feasible for use in the near term, at least for the Tier 0 and Tier 1 standards. This section discusses the emission control strategies EPA expects to be available and cost-effective at the time the locomotive emissions standards take effect. Additional information on locomotive technology and costs is included in the docket.[56,57]

Tier 0 Locomotives

Tier 0 locomotives are those originally manufactured from 1973 to 2001. Historically, two designs have dominated the locomotive engine market. The first is a two-stroke engine design using uniflow-scavenging and unit injection. The second is a four-stroke engine design using unit pump injection. Both designs are turbocharged and aftercooled for line-haul applications. There are also a few thousand Roots-blown[58] two-stroke engines and naturally-aspirated four-stroke engines used in switch locomotives.

Locomotives currently equipped with turbocharged engines will be able to employ modified/improved fuel injectors, enhanced charge air cooling, injection timing retard, and in some cases improved turbochargers, to reduce NOx emissions. Moreover, it will be practical and cost-effective to equip some of these locomotives with electronic controls as a means of avoiding the penalty in fuel efficiency often associated with injection timing retard. Within the category of improved fuel injectors, modifications are expected to include, injection rate changes, modifications to the injector spray patterns, and reduced sac volumes. Remanufacturers could also use limited modifications to the piston design, and enhanced smoke controls. Some of these technologies are already available. In 1994, two-stroke engines using electronically controlled unit fuel injectors were introduced into service in passenger locomotives

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[56] Acurex Environmental, “Locomotive Technologies to Meet SOP (sic) Emission Standards,” Prepared for the U.S. Environmental Protection Agency, Contract No. 68-C5-0010, August 13, 1997.

[57] Engine, Fuel, and Emissions Engineering Inc., “Cost Estimates for Meeting the Proposed Locomotive Emission Standards,” Prepared for the U.S. Environmental Protection Agency, September 12, 1997.

[58] A Roots-blower is a positive displacement pump driven by the crankshaft which is used to force air into the combustion chamber.

used in California. The electronics package is similar to a design used in heavy-duty on-highway diesel engines. Also in 1994, electronic fuel injection was offered as an option in four-stroke locomotive engines. Although there were some reliability problems with the initial system, these problems have been resolved.

Enhanced charge air cooling will also be available, most likely taking the form of improvements in existing air-to-liquid aftercooling systems. EPA expects that engine coolant will continue to be employed as the cooling medium in most cases, rather than a separate cooling system. Although this charge-air cooling should not be too difficult to implement, some additional aftercooling hardware may be necessary such as an additional pump and radiator and whatever lines and fittings may be necessary to reroute the engine coolant. In the late 1980's a four-pass aftercooler was introduced on some two-stroke designs, which proved to be more effective than the older two-pass design. EPA anticipates that it will be cost-effective to replace nearly all remaining two-pass aftercoolers with four-pass aftercoolers during the remanufacturing process.

Overall, it appears likely that remanufacturers will achieve as much cooling of charge air as possible, improve fuel systems and combustion chambers, while using timing retard to the least extent possible so as to minimize negative effects on fuel consumption. Some four-stroke engines may require improved turbochargers to overcome problems with smoke during acceleration.

In the case of naturally-aspirated and Roots-blown engines, the tools available to manufacturers for reducing emissions are modifications to the fuel system, modifications to the combustion chamber and injection timing. In theory, these engines could be retrofitted with turbochargers and charge air coolers, which if fueling rates were not changed, would not increase power ratings and would lower peak combustion temperatures and thereby NOx formation. Most of these locomotives are employed in switching and terminal applications. It is probable that many of these will be replaced with lower horsepower line-haul units as the latter are replaced with newer, higher power units, per the current railroad practice.

Tier 1 Standards

Tier 1 locomotives are those that will be manufactured in 2002 through 2004. Tier 1 locomotives will be able to incorporate the technologies outlined above for the Tier 0 locomotives, but these technologies will likely be more effective in the Tier 1 locomotives because more optimization will be possible when they are included in the original design than is possible with retrofit technology. There are additional approaches that should also be available; these are discussed below.

Several recent locomotive models have already shown relatively low emissions of HC, CO, and PM, and will be able to achieve significant NOx reductions through minor incremental changes. These changes include a comprehensive emission management system consisting of optimized fuel injection strategies through the use of electronic controls and incorporation of separate circuit aftercooling. Separate cooling systems, which have been introduced in recent years, have resulted in enhanced effectiveness of the aftercooler. In these systems, separate circulation pumps and radiators are used for the aftercooler rather than for the engine's power assemblies. Therefore, the coolant to the aftercooler is not subject to the heat added by the engine.

Other technologies can be applied to many locomotive engines in addition to electronic controls and enhanced aftercooling. Through the use of electronics and enhanced aftercooling, further timing retard can be used to reduce NOx without a negative impact on PM. Additional technologies that will be available for some models include in-cylinder and turbocharger modifications. Changes in the configuration of the combustion chamber and piston ring location may begin to appear in engines complying with the Tier 1 standards. Increased compression ratios could be used to reduce PM emissions and ignition delay. In addition, upgraded turbocharger designs would help reduce smoke emissions by providing an improved response to transience.

In the case of switch locomotives, two approaches appear to be available to manufacturers. One approach would be the continued use of large displacement naturally aspirated engines employing electronic control of the fuel system, improved fuel injection and improved combustion chambers. Another approach would be to use turbocharging and other technologies used on line-haul locomotives, but with a reduction in engine size to achieve the desired lower power rating. A reduction in engine size could be achieved either through the use of fewer power assemblies of the same configuration as those used on line-haul locomotives or by the use of a different engine design than that used in line-haul applications. Locomotive manufacturers could also use large nonroad engines (1000-2000 hp) that were originally designed for use in non-locomotive applications. As with all other design choices, manufacturers will base final decisions on costs (both initial and fuel usage), on durability, and on serviceability and maintainability with respect to the availability of parts common to both switch and line-haul locomotives. There is also the possibility, given the ability of railroads to use older line-haul locomotives as switchers, that manufacturers could choose to not offer new switch locomotives during the Tier 1 period.

Tier 2 Standards

The Tier 2 NOx standards will require HC and PM control as well as additional NOx control. These standards will apply to locomotive engines originally manufactured in 2005 and later.

Locomotive engine manufacturers have been in the process of developing new engine designs with a focus on fuel economy and significantly increased power output, to take advantage of developments in traction motor technology. In the past, locomotive engines have been limited to about 4000 hp. This limitation was a direct result of space constraints associated with the axle-hung DC motors. However, the advent of high-performance AC motors has resulted in the availability of traction motors that have a much higher power density than the old designs. As a result of this change from DC to AC traction motors, new locomotive engines which are capable of up to 6000 hp are now under development by the two major locomotive manufacturers.

Because they are in the process of developing these new engine models and have been for several years, locomotive manufacturers are in a good position to meet the Tier 2 standards. Both of the high-power engines currently under development are four-stroke engines. (It should be noted that particulate emissions from two-stroke engines have been observed to be largely made up of entrained lubricating oil.) Four-stroke engines, however, have shown lower PM emissions because they generally achieve much better oil control. Furthermore, the best approach to designing engines inherently lower in emissions and most effectively implementing such strategies is to build them in from the beginning rather than adding them later in the process of a retrofit. This is true for the fuel management, combustion chamber, charge air cooling, electronic control, and other strategies discussed below and in Chapter 4.

A table listing potential Tier 2 technologies and resultant emission reductions is presented in Chapter 4. In general, EPA expects that additional NOx and PM emission reductions will be possible in these locomotive engines through continued refinements in charge air cooling, fuel management, and combustion chamber configuration, in conjunction with further improvements in electronic control systems. Improved fuel management would include strategies such as increased injection pressure, optimized nozzle hole configuration, and rate-shaping. Potential combustion chamber redesigns include the use of reentrant piston bowls and increased compression ratio. It may also be possible to reduce oil consumption by optimizing the ring pack design and bore honing technique. However, reduced oil consumption could require the use of more advanced oils to achieve comparable lubrication. Also, while EPA anticipates that locomotive engine manufacturers will strive to avoid using EGR to the greatest extent possible, the Agency believes that moderate rates of EGR may be used in some instances. When the engine is operating at the lighter load steady-state notches, EGR becomes a more attractive strategy. At these conditions, more excess air is available, so engine performance and PM emissions are less sensitive to EGR. Because the operation is steady-state, it makes optimization of the EGR and the fuel and air much easier that for an engine operating under transient conditions.

Many of the more advanced technologies mentioned in section 3.3 do not appear in the list of technologies that EPA expects will be used for compliance with the Tier 2 standards. This is because EPA cannot confidently project that the technical and/or practical obstacles to these technologies will be overcome. However, it should be remembered that the Tier 2 standards will not take effect for another seven years. This represents a substantial amount of lead time, which will provide an excellent opportunity for additional technological advances. Two emission control strategies that have shown some promise are selective catalytic reduction and alternative-fueled engines. These technologies and others in even more preliminary stages of consideration may ultimately prove to be more attractive emission control alternatives with sufficient development. Nevertheless, EPA cannot conclude that these technologies will be available in the time frame being considered.

3.5 Adjustments for Ambient Conditions

Manufacturers and remanufacturers can incorporate various technologies to account for changes in ambient conditions. The effects of changes in ambient temperature can be minimized by controlling the rate of heat rejection in the aftercoolers and engine cooling system. Current locomotives are already designed to have a fairly constant engine coolant temperature over a broad range of temperatures. This is achieved primarily by varying the flow of air past the radiator. Greater control at cooler temperatures is possible using a thermostat type system to bypass or partially bypass the heat rejection components of the cooling system (e.g., radiators) unless the coolant reaches the appropriate temperature. The potentially adverse effects of higher ambient temperatures can be reduced by increasing the cooling capacity of the engine, where possible.

The effects of low barometric pressures can be minimized either by reducing the amount of fuel injected or increasing the amount of air forced into the cylinder so that the appropriate excess air ratio can be maintained. Although reducing the amount of fuel injected at lower barometric pressures can result in maintaining emissions compliance, a loss in engine power usually results. Current diesel engine designs have been reported to operate with 24 percent less power and 5 percent higher specific fuel consumption at elevations approaching 7,000 feet.[59] An intermittent supercharger has been developed for truck engines that assists the turbocharger at high altitudes to compensate for lower air density effects.[60]

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[59] Lizhong, S., et al., "Combustion Process of Diesel Engines at Regions With Different Altitudes," SAE Paper 950857, 1995.

[60] Kapich, D., "Very High Speed Hydraulic Driven Supercharging System," SAE Paper 951822, 1995.

3.6 Reliability and Durability

EPA understands that the reliability and durability of locomotive engines are important to the railroad industry. Any time that a locomotive breaks down on a track, it can result in severely disrupted traffic flows, especially where the locomotive must be repaired in place. The technology projected to be applied to meet the locomotive standards has been applied to trucks and other applications. Experience to date suggests that there is no reason that any of these technologies should inherently cause any sort of reliability or durability problem for locomotives.

Although the emission control technologies described above are themselves likely to be inherently reliable and durable, there may be a learning curve associated with confidence in the application of these technologies to locomotives. With the seven years of lead time given in this rule, potential learning curve difficulties should not be a limiting factor. There will be adequate time for prototypes to be durability tested, for demonstration fleets to prove out the reliability of these technologies, and for upgrades and optimization to be implemented. Because of the importance of engine reliability and durability to the railroad industry, EPA believes that locomotive manufacturers will make sufficient efforts to prove out their new engine designs.

4.0 Emission Standards and Supporting Analyses

This chapter describes the development of EPA's emission standards for locomotives. As will be described, the regulations require that cycle-weighted brake-specific HC, CO, NOx, and PM emissions from each new locomotive be: 1) below the line-haul standards when weighted using line-haul duty-cycle; and 2) below the switch standards when weighted using switch duty-cycle[61]. The regulations also require that smoke emissions be below the specified smoke standards. Compliance with these standards is required throughout the full useful life of the locomotive. This chapter also describes the development of the duty-cycles, useful life periods, and baseline emission rates on which the numeric standards are based. Finally, this chapter also analyzes feasibility of these standards.

4.1 Duty-Cycles[62]

EPA believes that the most cost-effective means of achieving national locomotive emission reductions is to set standards for emissions weighted by typical in-use duty-cycles. Unlike other vehicles which have a continuously variable throttle, locomotives are limited to a predetermined number of throttle notches. Individual standards for each throttle notch might be able to achieve similar emission reductions, but with less flexibility, and thus, probably at a higher cost. This section describes the development of the two duty-cycles used in this regulation, as well as the development of a passenger locomotive duty-cycle that is presented here for informational purposes.

Industry Freight Locomotive Duty-Cycles

Industry has historically used two distinct types of duty-cycles for freight locomotives: line-haul and switching. The term line-haul refers to the movement of freight between cities or other widely separated points. Several previously-used line-haul duty-cycles are shown in Table 4-1. Switching refers to the process of assembling and disassembling trains in a relatively small area (a switchyard); thus switching operations are also often referred to as yard operations. Two historical duty-cycles for switch locomotives are shown in Table 4-2. Dynamic braking is not included in these cycles because switch locomotives are usually not equipped with this function.

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[61] Exception: existing switch locomotives will not be required to comply with the line-haul duty-cycle standards.

[62] For locomotives, a duty-cycle is a usage pattern expressed as the percent of time in use in each of the throttle notches.

Table 4-1

Historical Information -- Line-Haul Duty-Cycles
(Percent Time in Notch)

Throttle Position	GE Min.	GE Max.	GE Average 1	GE Average 2	EMD Heavy	EMD Medium	AAR
Idle	59.0	40.0	54.0	53.0	41.0	46.0	43.0
Dynamic Brake	1.5	7.0	4.0	5.5	8.0	9.0	8.0
1	6.5	2.5	5.0	5.1	3.0	4.0	3.0
2	6.5	2.5	2.5	3.9	3.0	4.0	3.0
3	6.5	2.5	2.0	3.4	3.0	4.0	3.0
4	6.5	2.1	5.0	3.3	3.0	4.0	3.0
5	2.9	1.8	2.0	2.8	3.0	4.0	3.0
6	2.9	1.8	2.0	3.4	3.0	4.0	3.0
7	2.5	1.8	2.5	2.6	3.0	4.0	3.0
8	5.2	38.0	21.0	17.0	30.0	17.0	28.0

Table 4-2

Historical Information -- Switch Duty-Cycles
(Percent Time in Notch)

Throttle Position	ATSF	EMD
Idle	77.0	77.0
Dynamic Brake	0.0	0.0
1	10.0	7.0
2	5.0	7.0
3	4.0	4.0
4	2.0	2.0
5	1.0	1.0
6	1.0	0.5
7	0.0	0.5
8	0.0	1.0

EPA Duty-Cycles

In response to a request by EPA, several freight railroads collected time-in-notch data for both line-haul and switch operations. Amtrak also collected data for passenger locomotive operations. The data were presented to EPA in different formats, but each allowed the calculation of average time in each notch.[63] It is important to note that not all of the idle time reported corresponds to time during which the locomotive was not moving. As much as one-third of idle time can be spent while a locomotive is coasting (i.e., moving forward because of either gravity or momentum without any power being applied to the traction motors).

In the case of line-haul operations, the data came from 63 trains[64] operated by five Class I railroads. Train operations were spread over many regions of the nation and represented approximately 2,475 hours of freight train operations. Data on switch operations came from two railroads and represented approximately 333 hours of switch locomotive operations. Amtrak provided data from 20 locomotives covering approximately 57,500 hours of operation.

These data were reviewed to identify duty-cycles applicable to line-haul, switch and passenger operations. Results from the data collected by the railroads are summarized in Tables 4-3 through 4-5 below. In addition to the average duty-cycles developed from the current database, the highest and lowest individual percentages of the time in notch from all line-haul and switch locomotive data were shown in Tables 4-3 and 4-4. This information shows the presence of very wide variations around the averages for the two types of operations.

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[63] EPA assumed equal time is notches 1 and 2 because some of the line-haul data did not separate those notches from one another.

[64] The term train is used for line-haul, instead of locomotive, because many of the trains for which data were reported included more than one locomotive in the consist. For example, a given train could require 12,000 total horsepower for propulsion, which would be accomplished with three 4,000 horsepower locomotives in series.

Table 4-3

Current Locomotive Operations - Line-Haul Duty-Cycles
(Percent Time in Notch)
Data Source: 63 Trains

Throttle Position	Average	Highest	Lowest
Idle	38.0	77	1
Dynamic Brake	12.5	41	0
1	6.5	23	0
2	6.5	23	0
3	5.2	13	2
4	4.4	11	1
5	3.8	12	0
6	3.9	11	0
7	3.0	18	0
8	16.2	39	0

Table 4-4

Current Locomotive Operations - Switch Duty-Cycles
(Percent Time in Notch)
Data Source: 8 Locomotives

Throttle Position	Average	Highest	Lowest
Idle	59.8	82	23
Dynamic Brake	NA	NA	NA
1	12.4	18	7
2	12.3	18	7
3	5.8	20	1
4	3.6	17	1
5	3.6	15	0
6	1.5	10	0
7	0.2	1	0
8	0.8	4	0

Table 4-5

Current Locomotive Operations - Passenger Duty-Cycles
(Percent Time in Notch)
Data Source: 20 Locomotives

Throttle Position	Average	Highest	Lowest
Idle	47.4	60	40
Dynamic Brake	6.2	8	2
1	7.0	11	5
2	5.1	6	4
3	5.7	7	4
4	4.7	6	4
5	4.0	5	2
6	2.9	6	1
7	1.4	2	1
8	15.6	19	8

The average line-haul duty-cycle from current operations is generally consistent with the historical cycles. Current operations, however, show higher usage of dynamic brake than in any of the historical cycles. In the case of switching operations, the current data show a lower percentage of time at idle and higher percentages of time in notches 1 and 2 than are shown in the historical cycles. The historical cycles bracket the results from current data for the other throttle notches.

EPA believes that it is more appropriate to use the results of the recent operational data for this rulemaking since their source is known (while the exact source of the information used to develop the historical cycles is not fully known). Moreover, the data are known to represent operations in widely dispersed areas of the nation. The three average duty-cycles (line-haul, passenger[65] and switch) are summarized in Table 4-6 below.

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[65] The passenger duty-cycle is not used in the regulations, and is shown here only for informational purposes.

Table 4-6

EPA Estimated Duty-Cycles for Current In-Use Locomotive
(Percent Time in Notch)

Throttle Notch	Line-haul	Passenger	Switch
Idle	38.0	47.4	59.8
Dynamic Brake	12.5	6.2	0.0
1	6.5	7.0	12.4
2	6.5	5.1	12.3
3	5.2	5.7	5.8
4	4.4	4.7	3.6
5	3.8	4.0	3.6
6	3.9	2.9	1.5
7	3.0	1.4	0.2
8	16.2	15.6	0.8

Emissions Impacts of Duty-Cycles

EPA believes that requiring locomotives to comply with emission standards using both a high-power duty-cycle (line-haul) and low-power duty-cycle (switch) will not only achieve cost-effective national emission reductions, but will also minimize the geographic variation in the reductions. The line-haul cycle is fairly representative of a national average duty-cycle. However, because it weights high-power emissions so heavily, it would be possible for a locomotive to comply with line-haul emission standards with little or no emission reduction at idle. This is not an unreasonable scenario to consider, especially for current locomotives, since the emission controls expected to be employed are generally most effective at higher power levels. If such a compliance strategy were allowed, then urban areas where locomotives are operated more frequently at idle and in low power notches could potentially see little or no emission reductions. This is why EPA is requiring that all locomotives be required to comply with emission standards for both the line-haul and switch duty-cycles.

It should be noted that while the idle weighting factors for the two duty-cycles are not that different from one another (0.380 and 0.598), the relative importance of idle emissions in the two cycle-weighted emission calculations is very different. This is because the calculation weights mass emission rates (g/hr), which can be nearly 100 times greater at full power (notch 8) than at idle. While idle emissions are not very significant for the line-haul cycle, they can actually be more important than notch 8 emissions for the switch cycle. For example, consider a locomotive that has mass emission rates of 700 g/hr at idle and 50,000 g/hr at full power. Using the line-haul weightings, the weighted emission rates for idle and full power would be 266 (700 x 0.380) and 8,100 (50,000 x 0.162) g/hr, respectively. In this case, the contribution of notch 8 emissions would be 30 times that of the idle emissions. On the other hand, using the switch weightings, they would be 419 (700 x 0.598) and 400 (50,000 x 0.008) g/hr, respectively. In fact, using the switch weightings, weighted emissions for all notches will generally be of similar magnitude. This means that manufacturers and remanufacturers would have a strong incentive to achieve significant emission reductions for each notch.

While the available data indicate that duty-cycles for passenger locomotives are different from those of freight locomotives, EPA believes that it is not necessary to use a passenger-specific duty-cycle to achieve the desired emissions reductions from passenger locomotives. The average passenger locomotive's duty-cycle is similar to the average line-haul cycle, except that it includes significantly more idling time. Thus, requiring all locomotives, including passenger locomotives, to comply with emissions standards for the line-haul and switch cycles should achieve essentially the same emission reductions as would be achieved by using the passenger cycle. Moreover, as noted previously, manufacturers and remanufacturers are likely to reduce emissions significantly in all notches, which would make duty-cycle concerns less significant.

4.2 Useful Life

Definition of Useful Life

Useful life is the term EPA uses to designate the period during which a vehicle is required to comply with emissions standards. For highway vehicles, the period of compliance is usually expressed in terms of years and mileage, with the requirement for compliance ending when either parameter is exceeded. Useful life periods currently applicable to highway vehicles were originally intended to approximately correspond to the median time and mileage at which a unit is scrapped or remanufactured. The range of current highway vehicle useful life values are from 10 years and 100,000 miles for light-duty vehicles (passenger cars) to 10 years and 435,000 miles (beginning in 2004) for heavy heavy-duty diesel engines (i.e., engines used in largest trucks).

For locomotives, EPA is explicitly defining useful life to be the period during which a locomotive is designed to remain properly functional with respect to power output and fuel economy. This definition recognizes that different designs of locomotives can have different useful lives. EPA's approach is to specify default useful life values, but require manufacturers and remanufacturers to specify longer useful lives for locomotives that are designed to last significantly longer than the default period. In some limited cases, EPA will also allow remanufacturers to specify shorter useful lives for locomotives that are designed to last significantly less than the default period, provided that the manufacturer can provide adequate technical justification. This will only be allowed for engines that were designed for use in non-locomotive applications.

This design period is very similar to the average period between remanufactures, and takes into account the intense maintenance which most locomotives undergo in use and the strong desire on the part of railroads for reliability. Thus, EPA based its default useful life values on current information about remanufacturing intervals. However, EPA did not set the default values to be equal to current average remanufacture intervals. Rather, it projected future intervals, based on current average intervals for the more recent locomotive models, and on comments from industry regarding future technology.

Current Class I Remanufacturing Practices

Figure 4-1 shows remanufacturing interval data provided by AAR.[66] Although these data were collected from a single railroad (ATSF), they are fairly representative of Class I remanufacturing practices for the current fleet. These data show a median remanufacture interval of about 20,000 MW-hr (about 5.7 MW-hr per hp), and that about 95 percent of locomotives are remanufactured before they reach 28,000 MW-hr (about 8.0 MW-hr per hp). Similar data for mileage intervals, which are shown in Appendix A, indicate a median remanufacture interval of about 700,000 miles.[67]

The figure also shows that there is an increase in the MW-hr remanufacturing intervals for newer model locomotives. To some extent, this is caused by an increase in engine horsepower. However, it also results from improved durability. Manufacturers have made numerous improvements over the years to significantly increase engine life. Railroads have also increased engine life by constantly improving maintenance practices. EPA expects that these trends will continue, resulting in marginal increases in median engine life each year.

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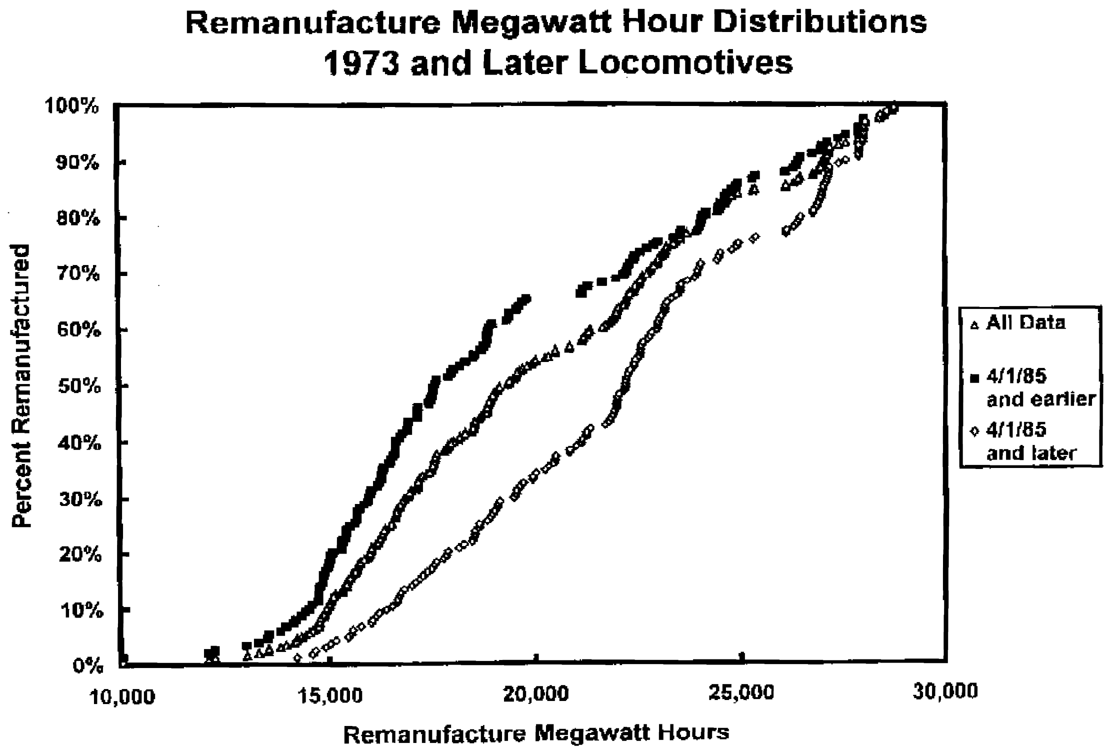
[66] Data are for ATSF remanufacturing between 1989 and 1994 of locomotives manufactured 1973-1990. Essentially all of the locomotives in this data set were between 3000 and 4000 hp, with an average of approximately 3500 hp.

[67] EPA received other similar data from AAR regarding remanufacturing intervals. These data have been placed in public docket A-94-31.

Figure 4-1


Remanufacture Megawatt Hour Distributions
1973 and Later Locomotives
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Percent Remanufactured
10,000
15,000
20,000
25,000
30,000
Remanufacture Megawatt Hours
△ All Data
■ 4/1/85 and earlier
◇ 4/1/85 and later

Default Useful Life

EPA believes that the most appropriate way to determine useful life is set default values, and then specify variations from that default on a case-by-case basis. EPA believes that the default values in MW-hr should be equal to 7.5 times the rated horsepower of the engine. For a typical 3500-hp locomotive, like those shown in Figure 4-1, this would mean a useful life period of 26,250 MW-hr.

In selecting this default value (i.e., 7.5 times horsepower), EPA sought a value that would generally be feasible for the current fleet, even if there are no future improvements in engine life, while ensuring the desired in-use control of emissions from future locomotives under the most likely engine life scenario. While the selected default value is somewhat greater than the median remanufacture interval for the current fleet, EPA is confident that remanufacturers will be able to comply with the standards during this period. EPA also believes that this value will be reasonably close to the median remanufacturing interval that will be observed for Class I railroads after these standards go into effect.

EPA recognizes that some Tier 0 locomotives will not be equipped with megawatt-hour meters. For these locomotives, EPA has set the default useful life at 750,000 miles, or ten years, whichever occurs first. EPA is including the year specification to account for switch locomotives, or other low-use locomotives. In practice, EPA expects that most Tier 0 line-haul locomotives will reach the 750,000 mile point before ten years, while most Tier 0 switch locomotives will not. Moreover, EPA is not confident that mileage accumulation values would be meaningful for switch locomotives operating within a switchyard, where miles have little relevance.

Variations From Default Values

EPA expects that some future locomotives will be designed to be operated (and actually will be operated in use) significantly beyond the default useful life values defined here. In such cases, EPA will require that manufacturers and remanufacturers specify a useful life that is longer than the default values. Generally, EPA would require that the useful life value be at least as long as the median remanufacturing interval of those locomotives in use. However, the Agency does recognize that there could be cases in which the median remanufacturing interval would not be appropriate for the useful life because the railroads were actually using the locomotives beyond their legitimate design life. Such special cases would be indicated by very significant increases in fuel consumption and/or decreases in reliability or power output, or excessive maintenance costs before the locomotives were remanufactured. Nevertheless, EPA believes these would be rare cases.

EPA will allow manufacturers of nonroad engines used to repower locomotives to petition for a shorter useful life. EPA recognizes that many of these engines will have been designed for other applications where they may not expected to last as long as a locomotive engine. In these cases, EPA will allow a significantly shorter useful life, but will require substantial supporting information from the manufacturer.

4.3 Baseline Emission Rates

Locomotive manufacturers (EMD and GE)[68] provided EPA with information on locomotive emissions for HC, CO, NOx and PM. Most of the information was provided at the time that EPA was developing revisions to the calculations for locomotive emissions in "Compilation of Air Pollutant Emission Factors, Volume II: Mobile Sources". The revisions to that document applicable to locomotives were published in 1992.[69] EPA weighted these data by both the line-haul and switch duty-cycles to estimate baseline emission rates. These cycle-weighted emission rates are shown in Appendix B with the individual notch emission rates. Shown in the Appendix G are the results of testing by Southwest Research Institute (SwRI) of late model locomotives. The NOx and PM emission rates are also shown in Figures 4-2 and 4-3, and summarized in Table 4-7. The HC and CO emission rates are shown graphically in Appendix H.

Table 4-7

Range of NOx and PM Emission Rates by Engine Type (g/bhp-hr)

	Line-Haul Cycle		Switch Cycle	
	NOx	PM	NOx	PM
EMD 645	11.5-18.2	0.25-0.31	14.1-33.1	0.28-0.44
EMD 710	10.6-14.2	0.23-0.35	14.2-17.3	0.28-0.39
GE	10.3-15.0	0.22-0.41	9.2-15.8	0.22-0.86

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[68] Note: some additional information was subsequently provided by Caterpillar, Inc., on a diesel engine appropriate for line-haul locomotives.

[69] Procedures for Emission Inventory Preparation, Volume IV: Mobile Sources; U. S. EPA, Emission Planning and Strategies Division, Office of Mobile Sources and Technical Support Division, Office of Air Quality Planning and Standards; EPA-450/4-81-026d (Revised).

In addition to the preceding information provided by manufacturers, information was made available to EPA by AAR[70]. The data supplied by AAR were collected by Southwest Research Institute (SwRI) under contract to AAR. Only a portion of the more recently provided information from AAR was utilized here since much of it was collected at only three power levels.

It is important to recognize that there is significant uncertainty associated with estimating baseline locomotive emissions, especially given the inherent variability of uncontrolled emission rates (e.g., line-haul NOx emission rates vary from 10.55 to 15.54 g/bhp-hr) and the limited amount of data that are available. The following analysis represents the Agency's best estimate of baseline emission rates.

Line-Haul Baseline Emission Rates

Line-haul emission rates were estimated for the 1990 fleet by cycle-weighting the emission rates of each engine type by their respective in use populations and horsepower. Similarly, weighted emission rates for later model locomotives were also calculated. However, the data used for these later model years were less complete. These analyses are summarized in Appendix C. EPA applied a deterioration factor to the weighted average HC and PM emission rates to account for the expected difference between average in-use emissions rates and emission rates calculated from test engines or relatively new locomotives; the weighted average HC and PM emission rates were multiplied by 1.15. This deterioration factor was estimated by EPA from its experience with other diesel engines, and from confidential business information provided by the locomotive engine manufacturers.

It should be noted that no attempt was made to account for potential differences in in-use usage rates (i.e., whether newer models are used more frequently than older models) for this baseline analysis. As can be seen from the data in the Appendices B and C, there no clear trend of emissions of older locomotives having very different emissions from the later model locomotives. The data from EPA's testing of several later model locomotives showed some evidence of higher NOx emissions and lower HC, CO, and PM emissions than were seen from the older locomotive models, but this trend was not conclusive. Nevertheless, in some cases, the NOx emissions from these newer locomotives were as high as 15 g/bhp-hr. Thus it is possible that, without EPA regulation, the average in-use NOx emission rate would be much higher in the future than is estimated for the current fleet.

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[70] Data have been provided by AAR on more than one occasion. The first set of data provided was collected in the early 1980s and was used in EPA's Report to Congress on emissions from locomotives. That set of data was not employed in development of this proposal because of its age.

Figure 4-2 Line-Haul Cycle Emissions Data

NOx and PM (g/bhp-hr)

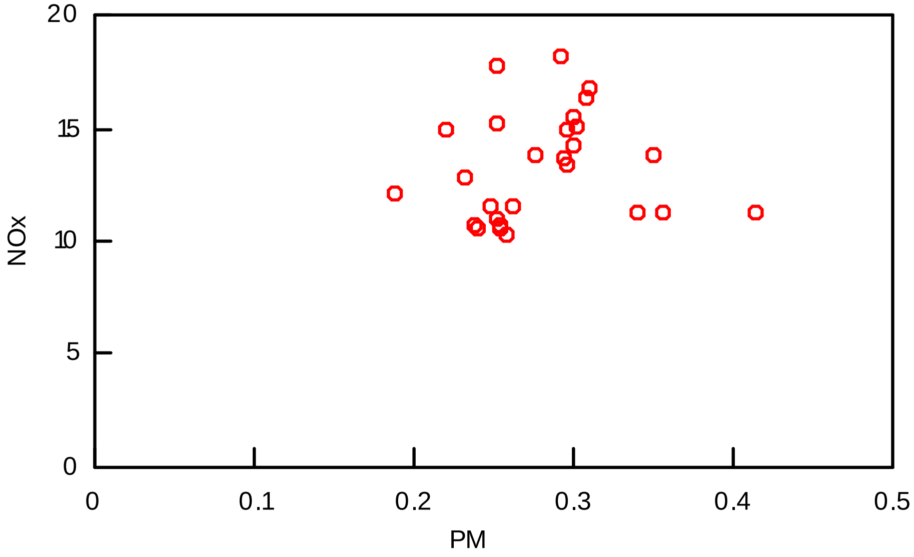
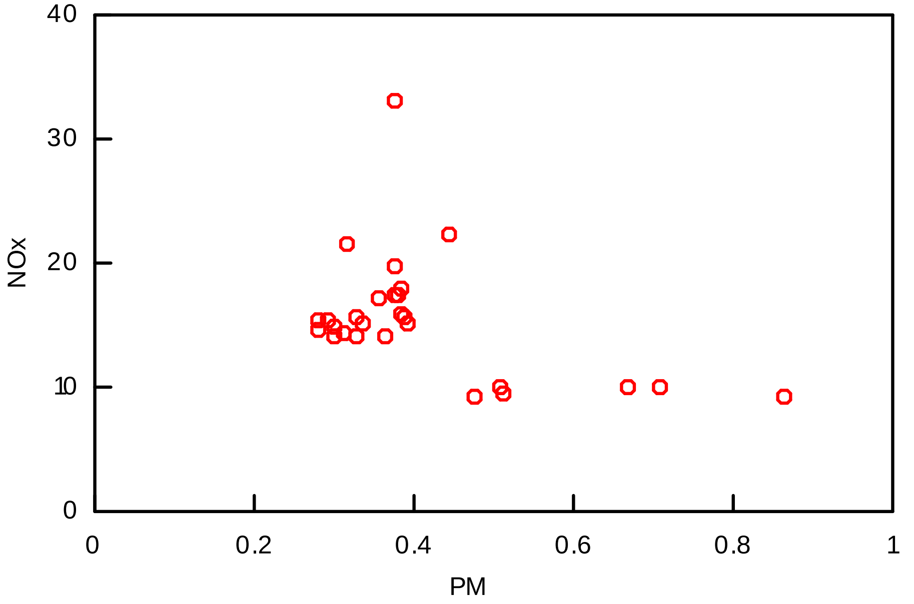


Figure 4-3 Switch Cycle Emissions Data

NOx and PM (g/bhp-hr)



Switch Baseline Emission Rates

Baseline emission rates for switch locomotives were estimated from cycle-weighted average emission rates for the three switch engine models that are used in the vast majority of existing switch locomotives. The same deterioration factor of 1.15 as was used in the line-haul analysis was also applied to the weighted average HC and PM emissions.

The following table presents estimated baseline emission rates for both line-haul and switch locomotives.

Table 4-8

Estimated Baseline In-Use Emission Rates (g/bhp-hr)

	HC	CO	NOx	PM
Line-Haul*	0.48	1.28	13.0	0.32
Switch**	1.01	1.83	17.4	0.44

* Line-haul locomotives over the line-haul duty-cycle

** Switch locomotives over the switch duty-cycle

Baseline Smoke Emissions

The available data for smoke emissions are summarized in Appendix D. These data are mainly for steady-state smoke levels. They show steady-state smoke levels ranging from 0 to 35 percent opacity for current locomotives (with standard injection timing) when measured with an optical path length of approximately one meter. Data for newer, well-maintained locomotives show steady-state smoke levels that are typically less than 10 percent.

4.4 Emission Standards

Gaseous and Particulate Emission Standards

The final emission standards for both the line-haul and switch duty-cycles are shown in Table 4-9. Also shown in the table are the expected design targets and average percent reductions from baseline emission rates. Based on the information currently available, EPA has concluded that these standards are the most stringent standards that can be achieved at a reasonable cost within the time period being considered. EPA is not necessarily projecting that all existing locomotive configurations will be able to achieve the Tier 0 NOx emission level at a reasonable cost, but rather that average NOx emission levels will be below the Tier 0 standard.

Full compliance will probably require significant use of the emission averaging, trading, and banking (ABT) provisions, and may require that some specific high-emitting engine configurations be converted to other configurations for which emission controls are more available. The Tier 0 standards for HC, CO, and PM will be achievable without averaging. For the Tier 1 and Tier 2 standards, ABT will be necessary for both NOx and PM since manufacturers may need this flexibility to ensure compliance for all freshly manufactured locomotives during the first few years. Absent ABT, less stringent standards or more lead time may have been necessary.

Given the emission control technologies that are expected to be available, EPA is establishing standards that will achieve very significant reductions in NOx emissions from the beginning of the program. However, the standards will not begin to achieve significant reductions in the emissions of other pollutants such as HC and PM until 2005. The Tier 0 and Tier 1 standards were set at levels that should allow the use of retarded injection timing, which may cause emissions of HC and/or PM to increase. This is appropriate because NOx is the only pollutant for which locomotive emissions contribute more than one percent of the estimated national inventories (locomotives contribute less than one-quarter of a percent for HC, CO, and PM). EPA did consider more stringent Tier 0 and Tier 1 emission standards for HC, CO, and PM, but concluded that the Tier 0 and Tier 1 emission standards for NOx might not be achievable if significant reductions in HC, CO, and PM were also required. Nevertheless, EPA does believe that *average* emissions for these pollutants will not increase, even though the standards will allow the emissions to increase for some specific locomotives. For these cases (which are denoted with asterisks in Table 4-9), EPA is projecting that average emissions will remain unchanged from baseline levels.

In considering what emission standards would be achievable, EPA also considered the need for compliance margins.[71] Based on data contained in Appendix E, it was assumed that manufacturers and remanufacturers would incorporate different compliance margins into the locomotive designs for different pollutants. The biggest compliance margin used was 20 percent for PM. The reasons for this are testing variability and the potential for in-use deterioration. For HC and CO, 15 percent compliance margins were used because of HC and CO measurement variability is significantly less than for PM. For NOx emissions, a 10 percent compliance margin was used because both deterioration and test variability are expected to be less of a concern for NOx than they are for other pollutants. This 10 percent margin is higher than the average compliance margin for 1993-1995 on-highway diesel engines that is shown in the Appendix E (8 percent) because EPA believes that manufacturers and remanufacturers will incorporate slightly larger compliance margins to account for the additional risk associated with the extensive in-use testing program.

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[71] A compliance margin is a difference between the emission standard and the design emission level. Manufacturers incorporate compliance margins to account for production and testing variability.

It should be emphasized that the estimated percent reductions are the reductions from the estimated 1990 baseline levels. As was noted earlier, there is some reason to believe that NOx emission rates would increase significantly (and HC and PM could decrease) in the future without these emission standards. Thus, the true reduction of the Tier 2 NOx standard, relative to some of the locomotives currently being produced, could be as high as 67 percent. The HC and PM reductions, on the other hand, could be somewhat lower.

Table 4-9

Emission Standards and Expected Emission Reductions

		Standard (g/bhp-hr)			In-Use Emissions (g/bhp-hr)			Percent Reduction		
		Tier 0	Tier 1	Tier 2	Tier 0	Tier 1	Tier 2	Tier 0	Tier 1	Tier 2
Line-Haul Cycle	NOx	9.5	7.4	5.5	8.6	6.7	5.0	34%	49%	62%
	PM	0.60	0.45	0.20	0.32*	0.32*	0.16	0%	0%	50%
	HC	1.0	0.55	0.30	0.48*	0.47	0.26	0%	3%	47%
	CO	5.0	2.2	1.5	1.3*	1.3*	1.3*	0%	0%	0%
Switch Cycle	NOx	14.0	11	8.1	12.6	9.9	7.3	28%	43%	58%
	PM	0.72	0.54	0.24	0.44*	0.43	0.19	0%	2%	56%
	HC	2.1	1.2	0.60	1.0*	1.0*	0.51	0%	0%	50%
	CO	8.0	2.5	2.4	1.8*	1.8*	1.8*	0%	0%	0%

* Baseline emission level

Smoke Standards

EPA is setting both "steady-state" and "peak" smoke standards for locomotives. These standards are shown in Table 4-10. The steady-state standards will apply to locomotive exhaust after the transition period during which the fueling rate is slowly increased (typically within 15 seconds) after a notch change. The peak standards apply to all times, but are intended to limit smoke during the transition period. The 3-second and 30-second standards apply to the maximum smoke level observed during any continuous 3-second and 30 second period, respectively. The same peak standards apply to all tiers of standards, while the steady-state standards become more stringent with each tier. There are several reasons for this. First, the Agency believes that steady-state smoke levels are more environmentally significant than peak levels for locomotives because of the largely steady-state manner in which locomotives are operated. Thus, it is more critical that the steady-state standards be sufficiently stringent. Second, EPA is more confident that Tier 1 and Tier 2 locomotives will be able to comply with more stringent smoke standards at steady-state than they will during the transition period after notch changes. Finally, EPA is concerned that overly stringent peak standards might adversely affect locomotive performance, and that such an effect might be unwarranted, given the marginal value of lower peak smoke standards.

Table 4-10

Smoke Standards for Locomotives
(Percent Opacity for One-Meter Path Length)

	Steady-state	30-sec peak	3-sec peak
Tier 0	30	40	50
Tier 1	25	40	50
Tier 2	20	40	50

Alternate Emission Standards

The general emission standards discussed previously are based on an analysis of the potential for emission reductions from diesel-powered locomotives. However, EPA recognizes that locomotives powered by alternatively-fueled engines could potentially have even lower emissions for some pollutants, while having difficulty complying with the standards for other pollutants. Therefore, EPA is establishing an optional alternate set of standards that could be applied to locomotives which operate on alternative fuels. The alternate standards allow higher CO emissions, but also require lower particulate emissions. Although these alternate standards are primarily intended to address issues associated with alternative fuels, EPA intends that they be available for application to any locomotive. Manufacturers and remanufacturers would be allowed to certify to the alternate CO standards instead of the normal standards, as long as they also comply with the more stringent alternate PM standards, as well as the normal NOx and hydrocarbon standards. They will not be allowed to mix the alternate CO standards with the primary particulate standards for a single engine family.

In developing these alternate standards, EPA focused on the emission characteristics of current natural gas-fueled locomotives. Such locomotives generally have higher (and more difficult to control) CO and hydrocarbon (i.e., total hydrocarbon) emissions than diesel-fueled locomotives, but lower PM emissions. The status of attainment for CO is much better nationwide than that for PM. Thus, it would be inappropriate to effectively defer the introduction of low-PM technologies like natural gas engines from market because they would have difficulty in complying with the CO standards. EPA believes that the environmental benefit of the additional PM reductions from these standards for this limited number of locomotives is greater than the environmental cost associated with allowing somewhat higher CO emissions.

4.5 Feasibility and Compliance with Standards

Manufacturers and remanufacturers will be required to comply with these standards during certification, production and in-use. This section discusses the ability of manufacturers and remanufacturers to comply with these requirements. Additional information regarding technological feasibility can be found in Chapter 3.

Tier 0 Certification

Table 4-11 outlines technologies that EPA believes will be available for retrofitting Tier 0 locomotives in 2000. The projected emission reductions listed in the table represent the reductions that would be expected for a typical Tier 0 locomotive. However, the existing fleet is diverse, and the effectiveness of these technologies will vary from model to model. Based on these projections, EPA has determined that the Tier 0 standards being adopted are the most stringent standards that can be adopted for the existing fleet. Both the manufacturers and the railroads have agreed with EPA that these standards are feasible, but that they will require extensive use of averaging, and may lead to a few locomotive models being removed from service. Compliance with the Tier 0 standards can be considered more precisely by dividing the subject locomotives into three groups: 1) older and low-volume locomotives; 2) recent and high-volume locomotives with relatively low PM and smoke emissions; and 3) locomotives requiring significant smoke and particulate control.

Remanufacturers of the first group of locomotives are expected to be able to comply largely by significant retarding of the injection timing. Such an approach, however, will result in a one to two percent increase in fuel consumption. The degree of timing retard needed can be lessened by using enhanced charge air cooling such as changing from a two-pass to a four-pass aftercooler. In some cases, remanufacturers of such locomotives are expected to use credits generated by other engine families with more advanced emission controls. For especially high-emitting locomotives, remanufacturers might also reconfigure the engine to more closely resemble other lower emitting configurations. Many improvements have been made over the last decade such as advances in fuel injection systems and turbocharger designs which could be applied to older engines. Also, it is expected that some of the old, inefficient locomotives will be removed from service instead of being rebuilt.

Manufacturers have indicated that, for most engine designs, the NOx emission standard is technologically feasible using technologies that can be incorporated during remanufacture. One locomotive engine design has shown unusually high emissions and is not expected to be able to meet the standard without more extensive retrofitting. However, the averaging and banking provisions of this rulemaking are expected to allow these locomotives to comply with the standard, especially since the number of these locomotives which are still in service is not very large.

Table 4-11

Tier 0 Locomotive Technology and Effectiveness
(Expressed as Percent Reduction from Baseline; Increases Shown in Parentheses)

Technology	HC	CO	NOx	PM	Smoke	BSFC
Timing retard	(5-15%)	(5-10%)	15-25%	(10-20%)	worse	(1-2%)
Electronic control	0-10%	--	0-10%	0-5%	better	0-1%
Fuel injection*	5-15%	5-10%	--	10-20%	better	0-1%
Improved turbocharging	0-10%	0-5%	(0-5%)	0-5%	better	0-0.5%
4-pass aftercooling	--	--	5-10%	0-5%	even	(0-1%)
Engine modification	0-5%	0-5%	--	0-5%	even	--
Puff limiter	--	--	--	--	better	--
COMBINED REDUCTIONS	10-20%	0-10%	30-45%	0-15%	better	(2)-1%

* improvements in nozzle geometry, sac volume, and fuel injection control for mechanical and electronic injectors

For the second group, where the number of locomotives within a family is high, or where the remaining service life is expected to be long, railroads are likely to desire higher technology remanufacturing kits that will minimize possible fuel consumption effects. To provide such kits, remanufacturers will likely use optimized electronic fuel injection systems that provide some of the NOx benefits of timing retard without the fuel consumption penalty. In some cases, remanufacturers will likely make some improvements to the aftercooling systems such as using four-pass heat exchangers. There are also opportunities for lower emissions and fuel consumption through the use of improved fuel injectors. Potential modifications to the fuel injection system would include injection rate, nozzle spray geometry, and reduced sac volumes. Since such approaches will likely result in NOx emissions well below the Tier 0 standards, many of these engines are expected to generate emission credits. Although many of the new locomotive technology improvements offer the potential for lower fuel consumption, some sacrifices may need to be made to fuel economy improvements to achieve lower emissions. Ultimately, each remanufacturer will make choices between first cost and fuel costs so as to minimize total cost of compliance over the remaining portion of the locomotive's total life.

Application of injection timing retard to the last group might be limited because of the PM and smoke increases that would result. However, turbocharger designs have improved in the past decade, and improved turbocharging allows for reductions in smoke and PM. In addition to improved turbochargers, such locomotives are expected to require significant improvements to aftercooling systems (e.g., more efficient heat exchangers) and electronically controlled fuel injection systems. They might also require combustion chamber redesign to reduce PM and smoke emissions by achieving more complete combustion. Some of these locomotives are expected to use NOx emission credits to the extent that they are available.

It is important to note that the ability of remanufacturers to fully comply with the Tier 0 emission standards is limited to some extent by their ability to devote adequate resources to developing emission controls for multiple engine families. Therefore, EPA is phasing-in the Tier 0 requirements to allow remanufacturers to focus their resources sequentially, beginning with the latest models. The initial focus on later model locomotives is appropriate because these locomotives are more heavily used than older locomotives. This approach has the additional benefit of minimizing market disruptions for small businesses that participate significantly in the remanufacturing of the older locomotives.

Tier 1 Certification

It is likely that both major locomotive manufacturers will be able to comply with the Tier 1 emission standards by further modification of their current production locomotives beyond the expected changes necessary to comply with the Tier 0 emission standards. The technologies that will be available are listed in Table 4-12. In addition, both major manufacturers are planning to introduce new low-emission locomotive designs, and have indicated that they will be able to comply with the Tier 1 emission standards by January 1, 2002. In fact, once optimized, these new locomotive models will be the models that the manufacturers use to comply with the Tier 2 standards. Thus, the manufacturers may be able to use these new models to generate emission credits, which could be used to ease compliance for their current models. However, even though EPA believes that some locomotive models would be able to comply with standards more stringent than the Tier 1 standards before January 1, 2005 (which is when the applicability of the Tier 1 standards ends for freshly manufactured production), EPA believes that the Tier 1 standards are the most stringent standards that will be feasible on average for all freshly manufactured production during the 2002-2004 time frame.

Table 4-12

Tier 1 Locomotive Technology and Effectiveness
(Expressed as Percent Reduction from Baseline; Increases Shown in Parentheses)

Technology	HC	CO	NOx	PM	smoke	BSFC
Timing retard	(10-25%)	(5-15%)	20-30%	(15-25%)	worse	(1-2%)
Electronic control	10-15%	0-5%	10-15%	5-10%	better	0-2%
Fuel injection*	10-20%	5-10%	--	10-20%	better	0-1%
Improved turbo-charging	5-10%	0-5%	(0-5%)	0-5%	better	0-0.5%
Separate circuit aftercooling	--	--	10-15%	0-5%	even	(0-1%)
Combustion chamber	0-5%	0-5%	--	0-5%	even	0-0.5%
Engine modification	0-5%	0-5%	--	0-5%	even	--
Puff limiter	--	--	--	--	better	--
COMBINED REDUCTIONS	10-20%	0-10%	45-55%	0-20%	better	(2)-2%

* improvements in nozzle geometry, injection pressure, sac volume, and fuel injection control for electronic injectors

Tier 2 Certification

Manufacturers will need to perform significant work to apply available on-highway emission control technology to locomotives to meet the Tier 2 standards. However, because the Tier 2 standards do not go into place until 2005, there will be a relatively long lead time thus sufficient opportunity for technological development, prove out, and certification.

On-highway diesel truck engines have shown large reductions in HC, NOx, PM, and smoke over the past 25 years while still increasing power and fuel economy. Many of the technologies developed for highway applications are expected to be able to be applied to locomotives. Therefore, much of the experience gained by the truck engine manufacturers can be applied to locomotive engine designs. Table 4-13 presents emission reductions achieved from heavy-duty on-highway diesel engines and those anticipated for locomotive engines.

Chapter 3 describes the technologies that will likely be used on locomotive engines to meet the Tier 2 standards. It should be noted that these are generally similar to systems being used on truck engines today. EPA believes that manufacturers would make use of some of these strategies regardless of emissions regulations in order to satisfy customer demands for higher power and better fuel economy. Given the long lead time, EPA believes that the manufacturers will be able to make use of these technologies to meet the Tier 2 standards. Table 4-14 includes the technologies that EPA expects will be used to meet the Tier 2 standards as well as the approximate effectiveness of each strategy.

Table 4-13

Emission Reductions for Trucks and Locomotives

	HC	CO	NOx	PM
On-Highway Heavy-Duty Diesel Engine History (HD-FTP transient cycle)				
1988 Truck Emission Standards (g/bhp-hr)	1.3	15.5	10.7	0.6
1998 Truck Emission Standards (g/bhp-hr)	1.3	15.5	4.0	0.1
2004 Truck Emission Standards (g/bhp-hr)	0.5*	15.5	2.0*	0.1
Percent Reduction Achieved in Past 10 Years	0%	0%	63%	83%
Percent Reduction Anticipated in 2004	62%	0%	81%	83%
Locomotive Engine Projections (based on line-haul cycle)				
Baseline Locomotive Emission Levels (g/bhp-hr)	0.50	1.3	13	0.32
Tier 2 Emission Standards (g/bhp-hr)	0.30	1.5	5.5	0.20
Design Target w/ Compliance Margin (g/bhp-hr)	0.26	1.3	5.0	0.16
Percent Reduction Required in 2005	47%	0%	62%	50%

* Nominal values, based on NMHC+NOx standard of 2.4 g/bhp-hr or 2.5 g/bhp-hr provided that NMHC does not exceed 0.5 g/bhp-hr.

EGR will likely be one of the primary technologies used by truck engines to meet future emission standards. However, EPA agrees with locomotive manufacturers that using EGR on locomotive engines at this time would require overcoming significant technical challenges. Moreover, EGR may not provide the same degree of emission reduction for locomotives as for trucks since it would not likely be used during high power operation which is more prevalent in the locomotive duty-cycle than the Federal Test Procedure transient cycle for truck engines. Nevertheless, it is possible that moderate rates of EGR may still be used in some instances.

Other technologies that may be on the horizon but are not expected to be available for widespread use in 2005 are SCR and natural-gas fueled engines. At this time, there are durability concerns associated with the vibrational and thermal stresses that would be seen by catalysts used in locomotive applications, and more investigation is needed on the durability and effectiveness of SCR. More investigation is also needed on both the operation of, and the fuel infrastructure needed for, natural-gas fueled locomotive engines. Nevertheless, EPA hopes that the potential to generate emission credits will provide an incentive for manufacturers and/or railroads to participate in demonstration programs that could ultimately lead to the viability of one or both of these technologies.

In summary, EPA believes that the NOx and PM standards established for Tier 2 locomotives are the most stringent standards that will be feasible in 2005. While EPA's analysis suggests that slightly more stringent standards could potentially be feasible if the effectiveness of each of the technologies listed in Table 4-14 were at the maximum level within the projected range, EPA believes that this is unlikely to be the case. In addition, there is some uncertainty in EPA's estimate of current baseline emissions. Thus, even if a 70 percent reduction in NOx emissions is ultimately possible, that does not guarantee that a 3.9 g/bhp-hr NOx emission rate (i.e., 30 percent of 13.0 g/bhp-hr) would be achievable. EPA believes that the NOx and PM standards being established appropriately balance the need for maximum stringency with the uncertainty inherent in the analysis.

Table 4-14

Tier 2 Locomotive Technology and Effectiveness
(Expressed as Percent Reduction from Baseline; Increases Shown in Parentheses)

Technology	HC	CO	NOx	PM	smoke	BSFC
Four-stroke cycle	0-10%	0-10%	--	0-20%	better	--
Timing retard	(10-25%)	(5-15%)	20-30%	(15-25%)	worse	(1-2%)
Electronic control	10-15%	0-5%	10-15%	5-10%**	better	0-2%
Fuel injection*	15-25%	5-10%	--	20-30%	better	0-1%
Rate shaping	0-5%	0-5%	15-25%	5-15%	even	--
Improved turbocharging	10-15%	5-10%	(0-5%)	5-10%**	better	0-0.5%
Separate circuit aftercooling	--	--	10-15%	0-5%	even	(0-1%)
Improved oil control	5-10%	--	--	5-15%	better	--
Combustion chamber	5-10%	0-5%	--	0-5%	even	0-0.5%
Puff limiter	--	--	--	--	better	--
COMBINED REDUCTIONS	50-65%	10-25%	60-75%	45-60%	better	(2)-2%

* improvements in nozzle geometry, injection pressure, and sac volume

** greater reductions would be expected during transient operation.

It is worth noting that EPA's analysis also projects reductions in HC and CO emissions that are larger than required by the Tier 2 standards. However, EPA believes that the projected emission reductions will probably be obtained even without tighter standards for HC and CO, since they are projected to result from the technologies required to comply with the PM standards. Given that the primary focus of this rulemaking has been to reduce NOx emissions, EPA believes that it would be inappropriate to risk compromising the feasibility of the NOx standards by setting very stringent HC and CO that could limit the ability of manufacturers to use injection timing retard to lower NOx emissions.

Production Line and In-Use Compliance

Compliance with the new emission standards during production will require that manufacturers and remanufacturers continue (or institute) proper quality assurance programs to limit deviation of production locomotives from the design specifications. Nevertheless, small but significant production variability is expected. As mentioned previously, EPA expects that manufacturers and remanufacturers will address this variability by incorporating compliance margins into their designs.

Because of the generally high expectations that railroads currently have for in-use locomotive performance in terms of power output, fuel consumption, and reliability, compliance with these standards in use during the full useful life is not expected to be significantly more difficult for manufacturers and remanufacturers than compliance at certification. In some cases, however, it may require somewhat more rigorous maintenance than some railroads are currently practicing. This will be especially true for Tier 1 and Tier 2 locomotives. Railroads may need to inspect, repair, and replace (as needed) fuel injectors or power assemblies more frequently than in current practice. They may also need to more carefully inspect the condition of the turbocharger and aftercooler systems and repair or replace these components more frequently.

High Altitude and High Ambient Temperature Compliance

Compliance with the emission standards under different ambient operating conditions may require that manufacturers and remanufacturers design their locomotives to be relatively insensitive to changes in ambient conditions or to adjust to such changes to the extent possible. Manufacturers and remanufacturers will need to continue their practice of designing control features into their locomotive aftercooler systems that minimize the effect of ambient temperature on the charge air and combustion temperatures. For barometric pressure (or altitude), manufacturers and remanufacturers will need to design control features into their locomotive fuel and/or charge air systems that will minimize the effect of ambient pressure on the engines air/fuel ratio. This will likely require either charge air designs that compensate for changes in ambient pressure, or deration of the horsepower out by decreasing the fueling rate. This technology is employed on many locomotives today.

5.0 Test Procedures

This section describes the Federal Test Procedure (FTP) for locomotives. Since the FTP is, in essence, a part of the emission standards, it is necessary for it to be very specific in order to minimize testing variability. Thus, the FTP should be considered the standard test procedure. However, as with EPA's test procedures for other vehicles and engines, the locomotive test regulations also allow alternate test procedures to be used, provided that they have been demonstrated to yield results equivalent or superior to those obtained from the FTP.

The FTP for locomotives is a nominally steady-state test procedure that measures gaseous (HC, CO, CO_2, and NOx), particulate, and smoke emissions from locomotives; that is, a procedure wherein measurements of emissions are performed with the engine at a series of steady-state speed and load conditions. Measurement of emissions would actually be performed during both steady-state operations and during the limited periods of engine accelerations between notches. The reason for this is that in-use locomotive operation is not truly steady-state. Rather, locomotive operation is a combination of short periods of largely steady-state operation at individual notches, and short transient periods between notch changes. In developing the final test procedure, EPA sought to ensure that all measured emission rates are representative of actual in-use emissions.

The test procedures, other than the test sequence, are based largely on the test procedures previously established for on-highway heavy-duty diesel engines in 40 CFR 86 Subparts D and N. Specifically, the raw sampling procedures and many of the instrument calibration procedures are based on Subpart D, and the dilute particulate sampling procedures and general test procedures are based on Subpart N. The most significant aspects of the test procedures are described below.

5.1 Locomotive Testing

In previous regulation of mobile sources EPA has based its emission standards on either chassis testing (e.g., on-highway light-duty vehicles) or engine testing (e.g., on-highway heavy-duty engines). In general, chassis testing is preferred because it more closely represents the operation of the vehicle in actual use. However, EPA recognizes that it can be impractical to require chassis testing for some sources. For example, EPA does not currently require chassis testing for on-highway heavy-duty engines because it would require an extremely large chassis dynamometer, and because a given engine model is often used in very different vehicle configurations. For this rule, EPA determined that it is appropriate to base the emission standards on chassis testing (or locomotive testing), as is described below.

Chassis Testing

Chassis testing for locomotives is reasonably practical because of the inclusion of electrical alternators as part of standard locomotive design. The power output of the engine, which is converted to electrical power by the alternator, can easily be dissipated as heat during an emission test. Thus, EPA believes that engine testing is not necessary, except for the few specific cases described in the "Engine Testing" section. Moreover, EPA believes that chassis testing offers significant potential advantages over engine testing; that is, there are problems that can occur with engine testing, but that would not be expected with chassis testing. First, the performance of engine coolant and intake air systems used during engine testing often deviate significantly from the performance of the actual locomotive systems in use. Second, engine test facilities are often designed with engine control systems that are different than the actual in-use systems. This is particularly important for smoke measurements, since one of the most common means of controlling smoke is to reduce the fueling rate during transients. Thus, if the fueling controls do not match the in-use fueling controls, then neither will the smoke measurements. Third, it can be difficult to simulate the actual in-use load on the engine during engine testing. Each of these three potential problems could significantly affect testing accuracy of engine testing. However, the most important problem with engine testing is that engine testing would be extremely impractical in use, because it would require pulling the engine out of the locomotive.

Engine Testing

EPA sees two cases in which it is somewhat reasonable to not require chassis testing of locomotives. First, it is acceptable to allow certification data to be generated from engine testing of a development engine. The concerns about accuracy are lessened to some degree by the fact that engine family would eventually be required to be chassis tested as part of the in-use testing programs. Similarly, EPA is willing to allow production line testing be conducted on the engine.

The Agency believes that when engine testing is conducted, it is critical that the testing be as representative of actual locomotive operation as can practically be achieved. Thus, EPA is requiring that important operating conditions such as engine speed, engine load, and the temperature of the charge air entering the cylinder be essentially the same as in a locomotive in use.

5.2 Test Sequence

Background

Locomotives differ significantly from road vehicles, in that the power from the engine is transmitted to the drive wheels by electrical and mechanical components, instead of only by mechanical components. With road vehicles, the relationship between engine speed (rpm) and vehicle speed (mph) is mechanically dictated by the gear ratios in the transmission and in the final drive. Locomotives, on the other hand, are powered by an engine through an electric alternator to electric motors that are connected to the drive wheels of the locomotive. The effect of this is that a locomotive engine is operated at a desired power output and corresponding engine speed without being constrained by locomotive speed. With the electrical coupling between the engine and the drive wheels of a locomotive, engine lugging is not possible.

Another design feature unique to railroad locomotive engines is the design and operation of the throttle. Power settings for railroad engines (throttle position) generally include eight discrete positions or notches on the throttle gate in addition to idle and the dynamic brake function. Each throttle notch position is numerically identified, with notch position one being the lowest power setting (other than idle) and position eight being maximum power. Because of this design, each notch on the throttle corresponds to a discrete setting on the fuel delivery system of the engine. These are the only engine power settings at which the locomotive can operate. The net effect of this method of control is that the engines can operate at only eight distinct combinations of fueling rate, power output and engine speed (in addition to idle and dynamic brake).

As described in Chapter 4, data collected by the freight railroads were recorded on throttle clocks with a capability for recording throttle position on a second-by-second basis. This allowed the analysis of the lengths of time that the throttle was continuously in each throttle notch. The data were reviewed to determine the continuous periods of time that locomotive engines typically remain at discrete power settings. These results are summarized in Table 5-1 for times continuously in notch. Inspection of the data shows that the time that locomotives are continuously operated at a given power level is typically relatively short. Only for idle, dynamic brake and notch 8 does the average time in notch exceed one minute. There are two reasons for this. First, it is often necessary for locomotives to slow down for safety purposes as they cross intersections in urban areas. Second , even when a constant locomotive speed is allowed, it often requires that the engineer constantly adjust the throttle to account for subtle changes in grade.

Table 5-1

Average Time Continuously in Throttle Notch (Minutes)

Throttle Notch	Line-Haul	Switching	All Operations
Idle	2.8	1.7	2.5
Dynamic Brake	5.6	NA	5.6
1	0.5	0.5	0.5
2	0.5	0.5	0.5
3	0.5	0.5	0.5
4	0.5	0.3	0.5
5	0.5	0.9	0.5
6	0.6	0.4	0.6
7	0.5	0.3	0.5
8	4.9	0.9	1.2

AAR provided continuous traces of NOx emissions from locomotives manufactured by both GE and EMD, under the following two conditions. First, starting with the engine at idle, NOx concentration in the exhaust was measured continuously as engine power was increased to full power and returned to idle. The time in each throttle notch was one minute during both increases and decreases in power. In the second test, the same sequence of power settings was employed but the time in each notch was increased to three minutes. Results from the testing performed are shown in Appendix M. The results of this testing showed: 1) that NOx concentrations in the exhaust during decreases in power repeated the values measured during increases in power, 2) that for current locomotive calibrations, equivalent NOx results would be obtained from the one minute in notch test and the three minutes in notch test, and 3) that the values obtained from the short times in notch tests equaled results obtained after prolonged periods of equilibration.

Sequence for Testing

The test sequence for locomotives and locomotive engines calls for the locomotive or engine to be operated at idle, dynamic brake and at the eight throttle notch positions. The test sequence begins with the engine at idle and at operating temperature and proceeds through dynamic brake and each power level to rated power. To begin the sequence, the engine is started, if not already running, and warmed up to normal operating temperature in accordance with warm-up procedures for in-service locomotives as specified by the manufacturer. For locomotive testing, the engine remains in the locomotive chassis, and the power output would be dissipated as heat from resistive load banks (internal or external). The engine is considered to be warmed up, and ready for emissions testing when coolant and lubricant temperatures are approximately at the normal in-service operating temperatures for these materials as specified by the manufacturer. After the engine has reached normal operating temperature, the engine is operated at full power (i.e., highest power notch) for 5 minutes, then returned to idle, or low idle if so equipped. Testing must be commenced within 15 minutes after the end of the 5 minutes of full power to prevent the engine from cooling off significantly. The 5-minute period at full power is intended to ensure that the engine is at a realistic operating temperature, and to improve test repeatability.

EPA is not including engine starting as part of the test procedure because the starting of locomotive engines which are fully cooled to ambient conditions seldom occurs in use. Locomotive engines tend not to be shut down, especially in cold weather, because it can be difficult to start these engines if they are allowed to cool to relatively low ambient temperatures and because of the potential for engine damage due to leakage of coolant. When the engines are shut down, restarts are generally performed before significant cooling of the engine occurs to avoid or minimize restart problems and coolant leakage problems.

Measurement of exhaust emissions, fuel consumption, power output, etc. begins with the locomotive idling, after the engine is warmed up. These measurements continue as the locomotive is operated in each notch. The minimum duration of each test point is 6 minutes, except for the maximum power point (notch 8), where the minimum duration of operation is 15 minutes. EPA concluded that longer periods of notch operation are not required to develop adequate test data. The most time-consuming requirement of emissions measurement is the time required to sample particulate matter. When the highest feasible particulate filter face velocity is employed, minimum sample time required to collect accurate particulate material samples from current locomotives is about four minutes per engine power level. This four minute value was increased to six minutes to provide sufficient time for accurate sample collection, especially under the Tier 2 standards for particulate emissions. In cases where a manufacturer is concerned about measurement variability, it will be allowed to perform replicate tests and to use the average of the replicate measurements. However, a manufacturer would not be allowed to replicate only tests that are high. If a manufacturer chooses to replicate tests, then it must replicate all tests.

It should also be noted that in-use locomotives are rarely operated continuously in a single notch for longer than these minimum sampling periods, especially for the intermediate power notches (1 through 7). Significant continuous operation for longer periods only occurs for idle, dynamic brake, and notch 8, but still accounts for less than a third of all operation. Such operation should not have any adverse environmental impact because the regulations prohibit any changes in the engine calibration after the sampling period that would increase emissions. It should also be noted that total mass emission rates (g/hr) for idle and dynamic brake are relatively low, and that long periods of continuous operation in dynamic brake and notch 8 are likely to be in rural areas. Both of these factors further minimize any potential for adverse environmental impacts from such operation.

In the event of test equipment failure during data acquisition, testing may be resumed by repeating the voided test mode, provided the engine is at normal operating temperature. EPA is allowing three approaches for ensuring that the engine is at normal operating temperatures. In the first approach, when a test mode is voided, the engine is returned to the next lower notch position (e.g., notch 3, if the notch 4 test mode is voided), and kept running in that notch until the problem is corrected. In the second approach, the engine is returned to idle while the problem is corrected, then the two test modes prior to the voided mode are repeated. With either approach, the sequence is then continued, starting with the voided test mode. The third approach is simply to start the test sequence over.

In order to minimize the testing burden, EPA is requiring that locomotives equipped with dynamic brake (DB) only be tested in one DB position. The DB position to be tested would be the notch generating nearest to 75 percent of the maximum braking capacity. This is the DB notch that EPA expects will be most environmentally important. While other DB positions would not have to be tested in the same manner, they would have to incorporate the same emission controls (see "Defeat Devices" section). Given that periods of dynamic brake use are limited, especially in urban areas, the potential for adverse environmental impacts from this approach is fairly minimal.

Similarly, for passenger locomotives that generate hotel power from the main propulsion engine, EPA is not requiring that testing for compliance be conducted with the engine producing hotel power. However, manufacturers and remanufacturers would be required to incorporate similar emission controls for hotel mode, especially in the area of injection timing (see "Defeat Devices" section). The Agency also retains the authority to require emission data collection from the locomotive or engine when it is generating hotel power.

Alternate Locomotive Configurations

The Agency recognizes that the potential exists for future locomotives to include additional power notches, or even continuously variable throttles, and is creating alternate testing requirements for such locomotives. Using the standard FTP sequence for such locomotives would result in an emissions measurement that does not accurately reflect their in-use emissions performance. Instead locomotives having additional notches would be tested at each notch, and the mass emission rates for the additional notches would be averaged with the nearest "standard" notch.

Locomotives having continuously variable throttles would be tested at idle, dynamic brake, and 15 power levels assigned by the Administrator (including full power), with average emission rates for two power levels (excluding full power) assigned to the nearest "standard" notch. The 15 power levels assigned represent one level for full power and two, to be averaged, for each of the seven intermediate power levels used on current locomotives. The Administrator retains the authority to prescribe other procedures for alternate throttle/power configurations.

Information provided to EPA by manufacturers on engine power levels in the various notch positions showed that the power in propulsion notches 1 through 8 followed a similar pattern when expressed as a percentage of the rated power of the engine. These power levels, which are shown in Table 5-2 below, would be used to adapt the normal duty-cycle weightings. As an example, for a locomotive equipped with 9 power notches (4, 11, 23, 35, 48, 64, 80, 90, and 100 percent of rated power), emissions measured from notches 1 through 6 would be weighted in the usual manner, notches 7 and 8 (80 and 90 percent of rated power) would be averaged and weighted by the normal notch 7 weighting factor, and notch 9 (100 percent of rated power) would be weighted by the normal notch 8 weighting factor.

Table 5-2

Typical Power Distribution by Notch

Throttle Notch	1	2	3	4	5	6	7	8
Percent of Rated Power	4.5	11.5	23.5	35.0	48.5	64.0	85.0	100

5.3 Sampling and Analysis

Gaseous Sampling and Analysis

Gaseous exhaust pollutants (HC, CO_2, CO, and NOx) are measured by drawing samples of the raw exhaust directly to chemical analyzers (with appropriate filtering). The sample is generally drawn through these analyzers using pumps that are located downstream of the analyzer. The sampling procedures are based on EPA's previous experience sampling diesel exhaust from on-highway heavy-duty engines (40 CFR 86). The required analyzers are: a chemiluminescence analyzer for NOx, a heated flame ionization detector (HFID) for HC, and a nondispersive infrared (NDIR) detector for CO and CO_2.

Testing of current locomotives has shown that exhaust concentrations generally reach their steady-state levels shortly after a notch change. Thus, EPA is requiring that a single steady-state concentration be used for gaseous emissions calculations, for each mode and each pollutant. EPA has created special provisions for locomotives that have long stabilization periods, which could require integration of the concentration in some cases. These provisions are criteria that specify when a steady-state emission measurement is considered to be representative of the typical period in notch. The criteria were developed so that a single steady-state value would be allowed for each mode for locomotives that reach their steady-state emission levels as soon after a notch change as most current locomotives do.

In order to ensure good reliability of test results, EPA is also establishing calibration and verification requirements similar to those applicable to on-highway heavy-duty engines. However, in these regulations, unlike the regulations for highway engines, the Agency is not establishing dilute sampling procedures for the total exhaust stream for gaseous emissions because it is not necessary to dilute the total exhaust stream prior to sampling with steady-state operation. In addition, the equipment that is required for dilute sampling would be very large and expensive. Nevertheless, not including such provisions does not preclude the use of dilute sampling as an alternative procedure.

Particulate Sampling and Analysis

Particulates are measured by drawing a sample of the exhaust through a filter and weighing the mass of particulate collected. Particulate sampling requires dilution of the sample to lower the temperature below 125°F, which minimizes evaporation of volatile particulate matter from the filters. The particulate sampling procedures are also based on the procedures found in 40 CFR 86. However, since the locomotive test cycle is essentially steady-state (and thus the volumetric flow rate of the exhaust is essentially constant for each test mode), the dilution and sampling systems can be simpler than are required for on-highway engine testing. The regulations do not require any critical flow venturi, or heat exchangers, since these are only used to maintain proportional sampling when the exhaust volumetric flow rate is changing continuously.

The regulations include specific requirements for the weighing of particulate filters. These requirements are intended to minimize contamination of the filters by dust or water vapor, which could otherwise lead to significant inaccuracy in the measurement. Also included in the regulations are recommended target loadings to ensure that sufficient particulate mass is collected to allow a meaningful measurement. Finally, the regulations include limits on the range of acceptable filter face velocities (i.e., the volumetric sample flow rate divided by the cross-sectional area of the filter) based on testing of on-highway engines[72] and industry comments.

Exhaust Ducting and Sample Probes

During locomotive testing, the exhaust emissions are routed through a metal duct, or exhaust stack extension, which is located directly over the exhaust outlet of the locomotive. It is important that the duct design is sufficiently open so that it does not cause any significant increase in the exhaust back pressure in the engine. The purpose of this duct is to prevent disturbance or dilution of the exhaust plume during sampling, and to provide for standardization of the sample probe location. The regulations call for the sample probes to be located in the duct between 2 and 5 feet downstream of the exhaust outlet during locomotive testing, or the nearest practical equivalent during engine testing. Although sample probe is not expected to have a large impact on repeatability, this specification is appropriate since it does not represent a significant burden. The allowance for different sample probe locations during engine testing is a recognition that issues such as safety or accessibility of the probes in engine test facilities may require that the probes be located more than 20 feet downstream of the exhaust outlet.

When testing locomotive engines with more than one exhaust outlet, the regulations require that all exhaust outlets be ducted together prior to sampling. However, for locomotive testing, it is not necessary to duct the exhaust outlets together, provided that a proportional sample is collected from each outlet, and a check is performed to ensure that the exhaust flows from each outlet are similar. More specifically, the regulations require that CO_2 concentrations be measured from each outlet, and that they be within 5 percent of each other. EPA believes that similar CO_2 concentrations are a reasonable indication that the exhaust flows are similar. Assuming that an engine was designed to have similar exhaust flows for each outlet, then the types of malfunction that would cause dissimilar flows should also cause

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[72] Guerrieri, D., V. Rao, and P. Caffrey, "An investigation of the Effect of Differing Filter Face Velocities on Particulate Mass Weight from Heavy-duty Diesel Engines," SAE Paper No. 960253, February 1996.

dissimilar CO_2 concentrations. For example, malfunctions that caused a loss of power in a given cylinder will typically lead to an increase in fuel consumption, as the engine controls increase the fueling rate in an attempt to maintain the power output. Such malfunctions would thus change the air/fuel ratio and should result in increased CO_2 concentrations for the exhaust outlet of the malfunctioning cylinder.

The three sample probe designs specified in the regulations are intended to collect a representative sample during testing. The basic designs have been successfully used previously for testing other diesel engines. The gaseous sample probe design is the same as is specified for general nonroad engine testing in 40 CFR 89. The dilute particulate probe design is the same as the design used for on-highway engine testing (40 CFR 86). The raw particulate probe design was used previously for diesel engine testing at SwRI. All three specific designs were tested for EPA at SwRI, and shown to work very well for locomotive emission testing.

Smoke Measurement

Smoke is measured with a smoke opacity meter mounted on top of the exhaust stack extension. The instrument specifications are the same as those used for on-highway heavy-duty engines. The meter measures opacity of the exhaust across the longest (nondiagonal) dimension of the extension. Emission measurements are normalized, using the following equation, to be equivalent to measurements made with an instrument that had a one-meter long (3.281 feet) path length. This equation is derived from the Beer-Lambert law that states that the logarithm of the transmissivity of a gas (i.e., one minus the opacity) is proportional to the path length.

$$N_n = 100 \times \left[1 - \left[1 - \frac{N_m}{100} \right]^{1/L} \right]$$

Where N_n is the normalized percent opacity, N_m is the measured percent opacity, and L is actual path length of the measurement system in meters (only that portion of the optical path that actually passes through the plume).

For simplicity, EPA has also included, as an appendix to the regulations, a table which allows an approximate comparison of measured smoke levels directly to the standard without normalization. This table shows comparable smoke standards for various path lengths in 10-centimeter increments. The comparable smoke standards were calculated from the low end of each range (e.g., 70.0 cm for the 70.0-79.9cm range), so that use of these standards for non-normalized measurements would not be less stringent than the official standard for normalized measurements.

Power and Fuel Measurement

Brake horsepower is the sum of the horsepower supplied to the main alternator and the mechanical horsepower required to operate accessories such as a secondary alternator. Power required to operate oil and fuel pumps, or to circulate coolant for the engine are not included in brake horsepower. The horsepower supplied to the main alternator is calculated as the product of the output voltage and current, divided by the alternator efficiency. The output voltage and current are measured directly using a voltmeter and current shunt. The alternator output may also be read from an onboard measurement system, provided that it meets the accuracy and precision requirements specified in the regulations. The alternator efficiency and accessory loads do not need to be measured during testing, provided that this information is supplied by the manufacturer or remanufacturer. The alternator efficiency must be expressed as a function of power input. The effect of temperature on the alternator efficiency must also be taken into account, where possible.

Fuel flow rates are determined by measuring the change in mass of an external fuel supply tank. For locomotive testing, the fuel intake and recycle lines are disconnected from the locomotive fuel tank and connected to the external tank. For many systems, a heat exchanger will be necessary to dissipate the heat from the recycled fuel. It is important to maintain a relatively constant fuel temperature, in order to obtain a stable measurement of the mass of fuel in the tank. Also, given currently available technology, a one-minute averaging period is recommended in order to obtain an accurate fuel flow rate measurement for all notches except idle, where a three-minute averaging period is recommended.

Natural Gas-Fueled and Alcohol-Fueled Engines

EPA is currently aware of only a few natural gas-fueled locomotives, and is not aware of any alcohol-fueled locomotives. Nevertheless, EPA believes that it is appropriate to include test procedures for such locomotives in these regulations. For this reason, the NMHC, alcohol and aldehyde measurement procedures that are currently applicable to on-highway natural gas- and methanol-fueled engines (40 CFR part 86) are being used for natural gas- and alcohol-fueled locomotives. EPA recognizes, however, the possibility of unforeseen problems that could result during the use of such procedures with locomotive engines, especially with alcohol-fueled locomotives (which currently do not exist). There is a lack of information on whether the specifications for dilute alcohol and aldehyde sample temperatures and flow rates are appropriate for locomotives, as well as a complete lack of such specifications for raw exhaust. Previous testing of highway vehicles has shown the potential for losses of alcohols and aldehydes through condensation if the sample line temperature is too low, or chemical reactions if it is too high. Nevertheless, at this time, EPA believes that it is appropriate to specify the on-highway procedures, but may reconsider alcohol and aldehyde sampling issues on a case-by-case basis, should alcohol-fueled locomotives come into use. Other aspects of the test procedure are the same as for diesel locomotives.

Calculations

The calculations specified for raw exhaust analysis are based on those in Subpart D of part 86. The algebraic form of some of the equations was changed slightly to clarify their meaning. Also, equations for both wet and dry analysis are included for each regulated species. The greatest change from the Subpart D calculations is that the calculation of the wet-to-dry conversion factor (K_W) is done in several steps, with iteration, instead of in a single equation. The calculation of DH2O is an algebraic solution of a hydrogen balance around of the engine, excluding hydrogen bound to organic matter in the exhaust. The sources of hydrogen are water entering in the intake air ($2Y \bullet DVol_{air}$) and hydrogen released from the fuel during combustion ($2\alpha(DCO2+DCO)DVol$, where DCO2 and DCO are volume fractions);[73] the small amount of hydrogen released from incomplete combustion reactions which do not produce CO_2 or CO is assumed to be negligible. The hydrogen in the exhaust is assumed to be in two forms: water and elemental hydrogen (H_2). The elemental hydrogen is assumed to be in equilibrium with respect to the following reaction:

$$H_2 + CO_2 = H_2O + CO \qquad \text{(equilibrium constant = K)}$$

The calculation of $DVol_{air}$ is an algebraic solution of a balance of the number of dry moles (excluding water) in the gas phase; the difference in the number of dry moles before and after combustion, neglecting H_2 formation and volatilization of the fuel, and assuming that all NOx produced is in the form of NO, is the amount of O_2 consumed minus the amount of CO_2 and CO produced. The calculation of DVol is an algebraic solution of a carbon balance of the moles of carbon coming into the engine (W_f/CMW_f) and the moles of carbon in the exhaust ($DVol \bullet V_m \bullet (DHC+DCO+DCO2)$, where DHC is the volume fraction of organic carbon ($ppmC/10^6$) and DCO and DCO2 are volume fractions ($ppm/10^6$)). The regulations also include an approximate non-iterative option for calculating K_W. This option uses an approximate calculation for DH2O that was recommended by the Engine Manufacturers Association in its comments on the NPRM.[74]

The calculations specified for dilute exhaust analysis are identical to those in Subpart N of part 86, except that the equations for calculating the dilution factor and the fraction of exhaust that is diluted (if partial dilution is used) are new. The dilution

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[73] Y = the water vapor concentration of the intake air expressed as a volume fraction; and α = the atomic hydrogen/carbon ratio of the fuel.

[74] Docket item #A-94-31-IV-D-36.

factor (DF) equation comes from a CO_2 balance around the dilution tunnel, and the fraction diluted (V_f) equation comes from a mass balance of the carbon in the diluted exhaust with the carbon coming into the engine in the fuel. The dilution factor is the ratio of the volume of dilution air to the volume of exhaust sample that is diluted. (The ratio of the total volume of dilution air plus exhaust sample to the volume of exhaust sample that is diluted is equal to one plus DF.)

5.4 Fuel Quality

Effects of Fuel Quality on Emissions

Changes in diesel fuel quality can have a significant effect on exhaust emissions. Perhaps the most important fuel parameter, with respect to emissions, is the weight fraction of sulfur in the fuel. Sulfur is a normal contaminant in crude oil and diesel fuel that is converted primarily to sulfur dioxide during combustion. A small amount of the sulfur, however, is converted to sulfate particulate. Thus, lowering the sulfur content of diesel fuel can lead to lower particulate emissions. A study by SwRI showed that lowering the sulfur content of diesel fuel from 0.315 weight percent (a typical in-use level for nonroad engine fuel) to 0.033 weight percent resulted in particulate reductions of 0.05 to 0.08 g/bhp-hr from uncontrolled locomotives.[75] Other studies have been less conclusive. It is important to note that, while the effect of sulfur on particulate levels is expected to vary from engine to engine because of different combustion properties, it should be relatively independent of total particulate levels. This is because sulfate particulate results from the oxidation of the fuel sulfur, rather than from incomplete combustion, which is the cause of organic particulates. It is known that railroads do occasionally purchase low-sulfur diesel for use in their locomotives, however, EPA is not aware of any reliable data regarding the relative amounts of high-sulfur and low-sulfur fuel used by the railroad industry. It is probable that the nationwide fraction of total fuel use that is low-sulfur is on the order of ten percent.

There are few data available on the effects of other fuel parameters on emissions from locomotives. However, data collected from on-highway heavy-duty emission testing have shown that increasing cetane number and decreasing aromatics content contribute to somewhat lower NOx and PM emissions. A combined reduction in aromatics content as well as an increase in cetane number was seen to give additional benefits in the reduction of NOx and PM.

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[75] Emission Measurements, Locomotives, Southwest Research Institute Report for EPA, August, 1995.

Test Fuel Specifications

The Agency is establishing test fuel specifications for compliance testing (certification, PLT and manufacturer/remanufacturer in-use testing) which are intended to be representative of in-use nonroad diesel fuel. More specifically, they are consistent with test fuel specifications for on-highway heavy-duty engine certification testing, with the exception of the sulfur specification. EPA is establishing a lower sulfur limit of 0.2 weight percent. The cetane and aromatics requirements are a cetane number of 40 to 48 and an aromatics content of at least 27 percent. These specifications are intended to approximate reasonable, but somewhat worst case in-use conditions. Since EPA is not regulating in-use fuel quality for locomotives, there is no reason to believe that in-use locomotives will use only low sulfur on-highway fuel, especially given the potential price differences between low and high sulfur diesel fuels, and potential availability problems in some areas of the country. Should EPA regulate in-use locomotive fuels in the future, it would also adjust the test fuel specifications as appropriate. It should be noted that any improvements in in-use fuel quality would also necessitate a reconsideration of the appropriate levels of the standards.

5.6 Atmospheric Conditions During Testing

As is described in Chapter 3, ambient conditions such as temperature, humidity, and barometric pressure are known to affect emissions from diesel engines. These test conditions need to be limited to some extent to keep the compliance burden for manufacturers and remanufacturers reasonable. However, in order to ensure that these regulations achieve the expected environmental benefits during normal railroad operations, and to allow for outdoor testing, EPA is specifying a fairly wide range of temperatures and pressures for testing, with no restrictions on humidity. The specified range of test conditions is an attempt to balance the environmental needs with those of the manufacturers and remanufacturers. An important factor which supports the wide range is that the large size of locomotives makes outdoor testing desirable. While indoor testing of a locomotive *engine* under controlled temperature conditions could reasonably be expected to be practical, testing of a complete locomotive indoors would be more costly and may prove to be very difficult to implement in many cases.

Specifically, EPA is establishing a range for the test temperature of 45-105°F. The upper limit temperature of 105°F is specified to address summer high temperatures throughout the southern and western areas of the country, and to facilitate testing of locomotives under most conditions which can occur over much of the nation during the summer. By choosing this upper limit for the test temperature, EPA expects to also address any potential loss in control of NOx emissions, and even PM and smoke, if charge air density decreases sufficiently at very high ambient temperatures. There is a potential for NOx emissions to increase at very high temperatures if the effectiveness of charge air cooling decreases at these high temperatures.

The lower limit for the test temperature (45°F) was based on: 1) the prevailing temperatures in the areas of the nation where locomotives are manufactured and remanufactured (e.g., Pennsylvania, Illinois and Idaho), 2) the fact that ozone pollution is essentially a warm weather problem, and 3) the potential test variability that could occur at lower temperatures. Under low ambient temperatures, the effectiveness of charge air cooling as a NOx control strategy can be expected to increase, especially if engine coolant is not used as the cooling medium. At the same time, some increase in PM and smoke emissions can be expected if excessive cooling of the charge air is allowed to occur. This lower limit should allow outdoor testing during much of the year, without unreasonable test variability problems. Acquisition of test data when prevailing ambient temperatures at manufacturers' or remanufacturers' facilities are below the lower test limit can be achieved by providing indoor facilities. EPA could also allow testing at lower temperatures, but only in cases where a manufacturer or remanufacturer can demonstrate that it would not result in any compliance advantage.

EPA also sees the need to include compliance with the standards up to 7000 feet above sea level to achieve control of locomotive emissions at high altitude. This is necessary because some emission control technologies suitable for the control of NOx emissions, e.g., delaying the start of fuel injection, will tend to exacerbate other emissions, e.g., PM and smoke, especially at high altitudes. The inclusion of equipment that would assure the same absolute pressure of the charge air in the intake manifold at both low and high altitudes would reduce or control this concern. However, there is a significant burden associated with testing over a very wide range of barometric pressures to demonstrate compliance, which EPA believes should be limited. Therefore, EPA is establishing a lower limit on ambient pressure of 26 inches of mercury for testing. This corresponds to an elevation of about 4000 feet above sea level. EPA is requiring compliance at higher elevations, but is only requiring an engineering analysis to demonstrate the performance of the locomotive emission controls at elevations between 4000 and 7000 feet (about 23 inches of mercury).

In the proposal, the Agency recognized the need to correct NOx emissions for the effects of humidity and temperature during testing, but it did not propose specific correction factors. EPA considered using the NOx-humidity correction factor that is currently being used for on-highway and general nonroad diesel engines (40 CFR 86 and 89), but concluded that the data upon which that correction factor was based are not adequate for this rulemaking. In particular, EPA had concerns about the applicability of data from older pre-control on-highway engines to current and future locomotives that incorporate NOx-reduction technologies. More importantly, however, the data are inappropriate as a basis for such correction factors for locomotives because the range of test conditions for locomotives being established is much broader than was used in the collection of that data. Therefore, EPA contracted with SwRI to provide an analysis that would support the development of locomotive specific correction factors. The contractor provided a partial analysis, which EPA used for this rulemaking, but was not able to complete the analysis before the rule was finalized. This partial analysis can be found in the docket.[76]

That analysis recommended the following correction factors for the effects of ambient humidity and temperature:

$$K_H = \frac{C_1 + C_2 e^{(-0.0143)(10.714)}}{C_1 + C_2 e^{(-0.0143)(1000H)}} \qquad K_T = \frac{1}{1 - 0.017(T_{30} - T_A)}$$

Where:

$C_1 = -8.7 + 164.5e^{-0.0218(A/F)}$

$C_2 = 130.7 + 3941e^{-0.0248(A/F)}$

H = The specific humidity on a dry basis of the intake air (grams of water per kilogram of dry air).

(A/F) = Mass of moist air intake divided by mass of fuel intake.

T_{30} = The measured intake manifold air temperature in the locomotive when operated at 30°C.

T_A = The measured intake manifold air temperature in the locomotive as tested.

It is important to note that the correction factor for temperature actually uses the intake air temperature rather than the ambient temperature. This is because it is the effect of ambient temperature on the intake air that matters most, but this effect is highly variable from locomotive to locomotive. EPA is not allowing correction for the

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[76] Docket item #A-94-31-IV-A-2.

effects of ambient temperatures above 86°F. For most current locomotives, ambient temperature does not significantly affect intake air temperature over a broad range of ambient temperatures. This may not continue to be true for future locomotives, and EPA does want to provide an adjustment that would "correct" for a poorly designed aftercooler system. Finally, EPA recognizes that changes in ambient temperature can have other effects on measured emission rates (other than the effect of intake air temperature), but does not have any information on the effects at this time.

Since the effects of humidity and temperature on NOx emissions from locomotives are not fully understood at this time, EPA has decided to include conservative default correction factors in the final rule (i.e., factors that are more likely to overestimate emissions rather than underestimate emissions), but to allow manufacturers and remanufacturers to use their own correction factors where they are appropriate for their specific locomotives. The correction factor being used in the final regulations (K_{NOx}) is the product of the temperature and humidity correction factors developed by the contractor ($K_T \cdot K_H$) multiplied by an adjustment factor (F) to address uncertainty in the estimated correction. The adjustment is defined as:

$$F = \left[1 + \sqrt{0.25(\log(K_T K_H)^2)}\right]$$

Thus, the final correction factor is calculated as:

$$K_{NOx} = (F)(K_T)(K_H)$$

The effect of this uncertainty factor is shown in Table 5-3. As can be seen from the table, the uncertainty factor is always greater than one, and becomes smaller as the correction factor becomes closer to 1.000. Thus, this factor appropriately accounts for the uncertainty in the correction, which is least for those test conditions which are closest to 86°F and 75 grains (or 10.71 g of moisture per kg of dry air).

Table 5-3

Adjustment to Correction Factors

$(K_T)(K_H)$	Uncertainty Factor	K_{NOx}
0.800	1.048	0.839
0.900	1.023	0.921
0.950	1.011	0.961
0.985	1.003	0.988
1.000	1.000	1.000
1.030	1.006	1.037
1.050	1.011	1.061
1.100	1.021	1.123
1.200	1.040	1.248

The Agency recognizes that the correction factors being established in these regulations may not be appropriate for the long term, but believes that they are appropriate at this time. During the first several years of this program, EPA expects that nearly all manufacturers and remanufacturers will perform engine testing rather than locomotive testing, and will therefore be able to perform all testing under controlled conditions where the effect of the correction factors will be small (i.e. near 86°F and 75 grains). Moreover, where the manufacturer or remanufacturer believes that the default correction factors penalize them, they will be able to develop and use their own correction factors. Nevertheless, EPA expects to refine these correction factors in the future when better information becomes available.

5.7 Other Issues

Defeat Devices

A defeat device is a device or element of design that reduces the effectiveness of emissions control during actual operation, but that does not significantly affect emissions control under test conditions, or affects it to a significantly lesser degree. Such devices are prohibited by the Clean Air Act. The procedures and penalties for a finding of a violation of the defeat device prohibition are detailed in the regulations. Penalties for a violation could be as much as $25,000 per locomotive per day. EPA recognizes a significant potential for the use of defeat devices in locomotives, especially those equipped with electronic engine controls. Some examples are described below.

The simplest example of a defeat device would be an electronically controlled engine that had two injection timing calibrations: a low emission calibration (e.g., retarded timing) that is used during testing, and a low fuel consumption calibration (e.g., advanced timing) that is used all other times. Such a device could easily recognize that a locomotive was being tested because there would be no power going to the traction motors.

A second potential defeat device would be a calibration that had high emissions just after a notch change, but had much lower emissions near the end of the test mode (e.g., five minutes after the notch change). This would allow the locomotive to be calibrated for low fuel consumption during the first few minutes, but still have a "steady-state" emission level that is reasonably low. This is significant because the six-minute sampling period required by this regulation is significantly longer than the typical time in the intermediate power notches in actual use. Thus, a locomotive could be operated in a high-emission/low-fuel consumption mode the majority of the time in use, and spend relatively little time in the low-emission mode. This issue is addressed to some extent by the steady-state stability criteria included in the test procedure regulations. Similarly, a calibration that advanced timing after the end of the sampling period would also be considered to be a defeat device.

It should be noted that EPA does recognize that, to a limited extent, manufacturers can have legitimate reasons for calibrations that change with time. Most notably, it is often necessary to increase the fueling rate slowly after a notch change in order to prevent smoke emissions. In these cases, the variability of the calibration generally lasts only a few seconds, and should not adversely affect any emissions. EPA would not consider such a calibration to be a defeat device, provided that the manufacturer could provide adequate technical justification at the time of certification.

A more subtle form of defeat device would be a calibration that varied significantly by notch to the extent that it would influence the operation of the locomotive, discouraging the use of certain notches. EPA believes that if a locomotive was calibrated with severely retarded timing in one notch, operators may rarely use that notch because of concerns about fuel consumption or power output. As with the previous example, EPA would consider such a calibration to be a defeat device, unless the manufacturer provided adequate technical justification for the calibration.

Passenger locomotives designed to provide hotel power from the traction engine create the potential for a defeat device because the engine can be operated in an infinitely variable mode, depending on the hotel power load being placed on the engine. Such an engine could be calibrated to have low emissions when generating no hotel power (i.e., the test condition), but have higher emissions whenever it generates hotel power. Such calibration would clearly be a defeat device.

If a locomotive engine was never subject to testing in the locomotive chassis, it is possible that the engine could be tested at slightly different conditions (e.g., fueling rate or load) than those at which it would be operated in use, and thus could have a completely different calibration and emission performance. This is one of the reasons why EPA believes that it is necessary that every engine model be subject to in-use chassis testing.

Finally, unnecessary loading of the engine at idle and during dynamic brake operations by means such as operation of cooling fans, etc., when not required for the proper operation of the engine or locomotive, would also be considered to be a defeat device. EPA expects that any loads imposed during testing will also generally be imposed during actual locomotive operations. By requiring that any such load be imposed in use, it is expected that concerns about maximizing fuel efficiency will curtail any unnecessary loading of the engine during testing.

Idle Shutdown

The Agency is finalizing a regulatory incentive for the development of an automatic shutdown mechanism that could shut off an engine automatically after some extended period of idling. (Current locomotive engines tend not to be shut down for long periods of time, especially in cold weather, because it can be difficult to start these engines if they are allowed to cool to relatively low ambient temperatures and because of the potential for engine damage due to leakage of coolant.) The approach would be to reduce the weighting factor for the idle emission rate for engines equipped with automatic shutdown mechanisms, but use the higher power weighting factor that is specified in the regulations. This approach would account for the emissions benefits of a shutdown mechanism whereas the standard calculations would not.

At this time, EPA is not establishing specific alternate weighting factors for these locomotives because it does not have adequate information to accurately predict how much idling time would be reduced by such a feature. The Agency expects that an automatic shutdown would not have much of an impact on idling time for newer line-haul locomotives because they rarely are left at idle for long periods of time. However, an automatic shutdown mechanism may have a very significant impact on idling time for switch locomotives. Nevertheless, even for switch locomotives, the impact is hard to predict at this time. The impact would be greater for locomotives that shutdown after a shorter period of time, or for applications in which long idling periods are more common. Thus, EPA will require that any manufacturer or remanufacturer desiring credit for an automatic shutdown mechanism demonstrate the average percent reduction of idling time that it would achieve.

This option is expected to be especially useful for compliance with the switch-cycle standards because the high idle weighting factor in the switch cycle (0.598) will put significant pressure on manufacturers and remanufacturers to reduce idling emissions. With this option, a manufacturer or remanufacturer would get the same credit for reducing the idle emission rate (g/hr) by half as it would for reducing idling time by half. For example, consider two locomotives: 1) a locomotive with an idle emission rate of 350 g/hr; and 2) a locomotive with an idle emission rate of 700 g/hr, but with an automatic shutdown mechanism that was shown to reduce idling time by half. Assuming that power output rates at all notches are the same, and that emission rates for all non-idle notches are the same, then the two locomotives would have the same calculated cycle-weighted emission rates. This is because the contribution of idle emissions to the cycle-weighted total would be 209 g/hr in both cases; (350)X(0.598) in the first case, and (700)X(0.598)X(0.5) in the second case. (Note: the weighting factor for the power output would be 0.598 in both cases.) The two cases would also be equivalent from an environmental perspective.

Correlation Criteria for Alternate Measurement Systems

EPA has included as an appendix to the regulations a set of recommended criteria for demonstrating equivalence of alternate measurement systems. The criteria specify the appropriate test procedures, number of replicate tests, and degree of correlation. These criteria are based on recommendations made by the Engine Manufacturers Association (EMA) in their comments on the NPRM.[77] The final criteria differ from EMA's criteria in that they allow less variation for systems that measure low (while EMA allowed 5 percent variation for both high and low measurements), and they include specific requirements for replicating outliers. It is important to note that these criteria are merely recommendations. Manufacturers are allowed to submit for EPA approval other types of data which they believe demonstrate equivalence. These recommendations, however, provide the manufacturers more certainty regarding the type of data that EPA will normally expect.

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[77] Docket item #A-94-31-IV-D-36.

6.0 Emission Benefits

This section discusses the emission benefits expected from this rulemaking.[78] Emission benefits are presented both in terms of percent reductions and tons of pollutants reduced annually. This analysis separately addresses the impacts of:

1) Class I (freight-only) line-haul locomotives
2) Class I (freight-only) switch locomotives
3) Class II and III locomotives
4) Passenger locomotives

Emission benefits were calculated in the following manner. First, as described in Chapter 4, controlled and uncontrolled emission rates for in-use locomotives were estimated. Average in-use emission factors were estimated by assuming purchase, scrappage, and remanufacturing behavior for each type of locomotive service. National emission inventories (tons per year) were calculated from the emission factors and fuel consumption data. Reductions were calculated from a projected 1999 baseline. It is important to note that locomotive use, purchase, scrappage, and remanufacturing schedules vary from railroad to railroad, and that they are all relatively sensitive to economic conditions. Therefore, this analysis, which is based on typical historical behavior, merely represents the Agency's best estimate of impacts given the information available at the time of the analysis.

6.1 Methodology

National emission inventories were calculated for each type of locomotive service by first multiplying the fuel consumption rates (gal/yr) by a conversion factor of 20.8 bhp-hr/gal[79] to obtain total fleet bhp-hr/yr values. These fleet bhp-hr/yr numbers were then multiplied by the applicable fleet average emission rates to calculate emissions inventories (tons/yr). The fleet average emission rates for each year were calculated based on the number of each type of locomotive projected to be in the fleet at the end of the respective year. The total reductions expected for each future year were

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[78] The results described in this chapter are identical to those found in the December 1997 version of this document, including several minor errors. Results of corrected analyses are contained in Appendix O.

[79] This conversion factor was calculated from data in the SwRI report. It thus represents the conversion factor for locomotives manufactured in the mid-1990s. Older locomotives would be expected to produce less useful work from each gallon of fuel (i.e., have a smaller conversion factor), while future locomotives are likely to produce more work from each gallon of fuel (i.e., have a larger conversion factor).

calculated by subtracting the expected controlled inventory from the estimated 1999 baseline inventory. Locomotive emissions and their contribution to the national inventories are shown in Appendix N. Based on the fuel consumption data shown in Chapter 1, EPA is assuming no growth in locomotive emissions after 1996.

Fleet average emission rates were calculated as weighted averages of uncontrolled, Tier 0, Tier 1, and Tier 2 emission rates. These emission rates were weighted by estimated relative classwide fuel consumption rates (e.g., the percent of total fuel consumed by Tier 1 locomotives in a given year). The relative fuel consumption rates for each class were calculated assuming that they were proportional to the product of number of locomotives(N_{loc}), average horsepower (HP_{avg}), and a relative use rate factor (F_{RU}) based on average locomotive age, as shown below.

$$RelativeFuelConsumption = \frac{(N_{loc})(HP_{avg})(F_{RU})}{\sum (N_{loc})(HP_{avg})(F_{RU})}$$

This part of the analysis was simplified for all locomotives other than Class I line-haul freight locomotives (i.e., switch, Class II/III, and passenger locomotives) by neglecting differences in average horsepower and relative use rates. This was done due to a lack of specific information for these classes. Emissions factors were weighted by only numbers of locomotives. This simplification does not significantly affect the overall analysis because the differences in locomotive horsepower and usage rates for these classes, as a function of the tier of applicable standards, are less significant than for Class I freight locomotives. Moreover, these locomotives are relatively minor contributors to the total national emission inventories.

The average baseline emission rates described in Chapter 4 were used for all future uncontrolled emission rates. EPA estimated average in-use emission rates for future controlled locomotives by subtracting a compliance margin from the level of each of the standards. However, because the standards for HC, CO, and PM emissions from Tier 0 and Tier 1 locomotives were set to prevent significant increases in these pollutants, rather than to require reductions, EPA used the baseline emission rates in the cases where the standards would not force emission reductions.

TABLE 6-1

Estimated Emission Rates for Class I Locomotives (g/bhp-hr)

		Line-Haul Locomotives	Switch Locomotives
HC	Uncontrolled	0.48	1.01
	Tier 0	0.48	1.01
	Tier I	0.47	1.01
	Tier II	0.26	0.51
CO	Uncontrolled	1.28	1.83
	Tier 0	1.28	1.83
	Tier I	1.28	1.83
	Tier II	1.28	1.83
NOx	Uncontrolled	13.0	17.4
	Tier 0	8.6	12.6
	Tier I	6.7	9.9
	Tier II	5.0	7.3
PM	Uncontrolled	0.32	0.44
	Tier 0	0.32	0.44
	Tier I	0.32	0.43
	Tier II	0.16	0.19

6.2 Class I Railroad Analysis

Assumptions

There are currently about 21,000 Class I locomotives being operated in the United States.[80] (AAR believes that this estimate is high; they estimate that there are less than 20,000 locomotives actively being operated currently.) About 17,500 of these locomotives were originally manufactured after 1972, and are thus subject to these

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[80] Official Locomotive Rosters and News, 1997 special edition-Class I railroads, James W. Kerr, July 31, 1997.

regulations. These locomotives are used primarily in line-haul service. Most of the roughly 3,500 older locomotives are used as switchers. Based on these numbers, EPA is projecting that, in 1999, Class I railroads will have about 15,200 post-1972 locomotives, and 1,300 older locomotives in line-haul service. EPA is also projecting that they will have about 2,500 post-1972 locomotives, and 2,000 older locomotives in switch service. It is assumed that by 2008 (i.e., within six years of the time that this rule takes full effect), nearly all 1973 through 1999 line-haul locomotives will have been remanufactured to meet EPA's standards for these locomotives and locomotive engines.

More specifically, EPA is assuming that 13,200 of the post-1972 line-haul locomotives will be brought into compliance with the Tier 0 standards by 2008, and that 2,000 post-1972 locomotives and all 1,000 older line-haul locomotives will have been removed from Class I line-haul service by 2010. EPA is also assuming that 3,000 Class I switch locomotives will be brought into compliance by 2017, including many older locomotives that will be repowered or upgraded, and that the remainder of the existing Class I switch fleet will have been removed from Class I service by 2024.

EPA is assuming that fuel consumption will remain constant at the 1996 level of 3.601 billion gallons per year.[81] EPA recognizes that there is a short-term trend of increasing fuel consumption, but is not confident that it will continue. The long-term trend is for fuel consumption to remain fairly constant. This is the result of continual improvements in locomotive fuel economy, which have offset the significant increase in ton-miles of freight hauled. EPA is also assuming that 7.5 percent of fuel consumption by Class I railroads is for switching.[82]

With respect to new production of freshly manufactured line-haul locomotives, EPA is assuming 400 new units for years 2000-2004, 600 new units for years 2005-2010, and 300 new units for all subsequent years. The higher number assumed for years 2005-2010, is because the two largest western railroads are expected to purchase large numbers of Tier 2 locomotives during this period in order to accelerate their introduction into Southern California. After this period, sales are expected to slow somewhat in terms of number of units due to the higher horsepower output of each locomotive. EPA is also projecting that switcher sales will range from 50 to 100 per year.

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[81] "Railroad Facts", Association of American Railroads, 1997 edition.

[82] "Railroad Ten Year Trends," Association of American Railroads, 1995.

Results

The results of the Class I emission analysis are summarized in Tables 6-2 (line-haul) and 6-3 (switch). More detailed results are shown in Appendix I. These results project a 44 percent reduction in NOx emissions from line-haul locomotives by 2010. Figure 6-1 shows those NOx emission reductions expected in the first ten years from each tier of locomotive. As can be seen in the figure, the majority of emission reductions during the first ten years of the program come from Tier 0 locomotives. Emissions from switch locomotives are not expected to decrease as rapidly as emissions from line-haul locomotives because of a slower fleet turnover rate to Tier 2 technology. (Although not shown in the figure, emission reductions from Class I switch locomotives are distributed similarly with respect to locomotive tier.) Significant reductions in HC and PM emissions are not expected until Tier 2 locomotives are phased into the fleet in large numbers.

Table 6-2

Results of Class I Line-Haul Emission Analysis[83]

	Emission (Metric Tons/Year)			Reductions (Metric Tons/Year)			Percent Reduction		
Year	HC	NOx	PM	HC	NOx	PM	HC	NOx	PM
1999	33,300	901,000	22,200	0	0	0	0%	0%	0%
2000	33,300	889,000	22,200	0	11,000	0	0%	1%	0%
2005	31,900	614,000	21,300	1,400	287,000	900	4%	32%	4%
2010	27,300	485,000	18,000	5,900	415,000	4,100	18%	46%	19%
2015	25,200	453,000	16,500	8,000	448,000	5,600	24%	50%	25%
2020	23,300	423,000	15,100	10,000	478,000	7,000	30%	53%	32%
2025	21,500	395,000	13,800	11,800	506,000	8,300	35%	56%	38%
2030	19,900	370,000	12,700	13,400	531,000	9,500	40%	59%	43%
2035	18,600	350,000	11,700	14,700	551,000	10,400	44%	61%	47%
2040	17,900	345,000	11,300	15,300	556,000	10,900	46%	62%	49%

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[83] The results shown in this table are the same as those found in the December 1997 version of this document. Results of corrected analyses are contained in Appendix O.

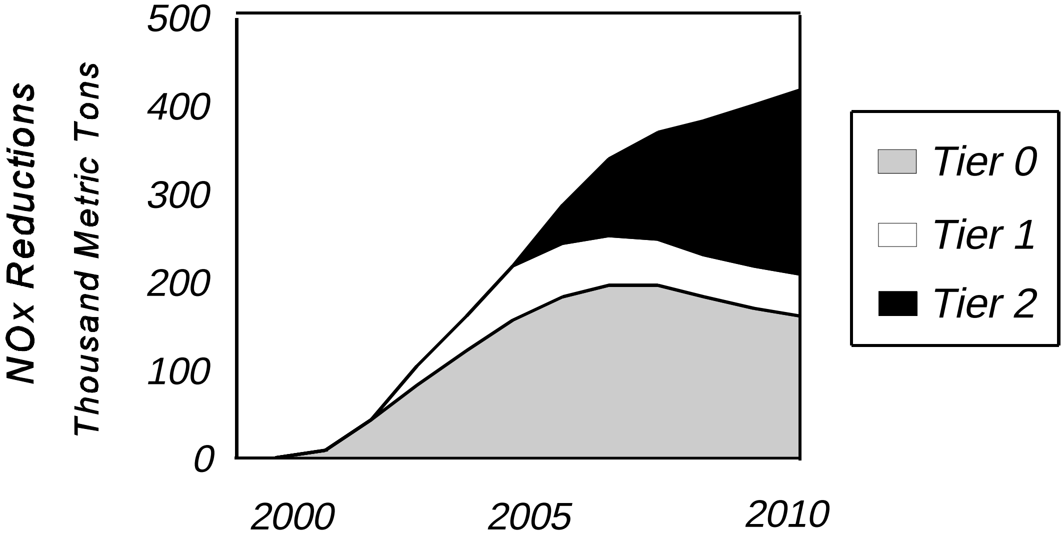
Table 6-3

Results of Class I Switch Emission Analysis

	Emission (Metric Tons/Year)			Reductions (Metric Tons/Year)			Percent Reduction		
Year	HC	NOx	PM	HC	NOx	PM	HC	NOx	PM
1999	5,670	98,700	2,470	0	0	0	0%	0%	0%
2000	5,670	98,700	2,470	0	0	0	0%	0%	0%
2005	5,640	90,900	2,460	30	6,800	20	1%	7%	1%
2010	5,470	81,400	2,370	210	16,400	100	4%	17%	4%
2015	5,260	71,200	2,270	410	26,500	210	7%	27%	8%
2020	5,030	65,200	2,150	650	32,500	320	11%	33%	13%
2025	476	60,500	2,020	920	37,200	460	16%	38%	18%
2030	4,440	57,200	1,860	1,230	40,500	610	22%	41%	25%
2035	4,040	52,800	1,660	1,640	44,900	810	29%	46%	33%
2040	3,580	47,900	1,430	2,100	49,800	1,040	37%	51%	42%

Figure 6-1

Class I Line-Haul NOx Reductions by Tier of Locomotive



6.3 Class II and III Railroad Analysis

Assumptions

Information provided to EPA by the American Short Line Railroad Association, which represents most of the Class II and Class III railroads, shows that there were approximately 4,200 locomotives in service with Class II and III railroads in 1994, and that they consumed about 215 million gallons of diesel that year.[84] However, only about 15 percent of these locomotives were originally manufactured after 1972. Based on these numbers, EPA is projecting that there will be about 600 post-1972 locomotives and 3600 older locomotives in the 1999 Class II and III fleet. Due to a lack of specific information, average Class II and III emission rates are assumed to be the same as the average emission rates for Class I line-haul locomotives. It is possible that actual emission rates could be somewhat higher since smaller railroads typically have lower power duty-cycles (i.e., more time at idle and low power notches, and less at notch 8), especially those railroads performing primarily switch and terminal services.

EPA is assuming that, during the first 10 years of the program (assuming that the remanufacture cycle for small railroads is about 10 years), Class II and III railroads will bring about 50 locomotives per year into compliance with the Tier 0 standards in order to have them covered as "new locomotives" by the CAA preemption provisions. EPA is also assuming that in 2012 these railroads will begin to purchase about 150 complying Tier 0 locomotives per year from Class I railroads. It is unlikely that they would be able to purchase any complying locomotives prior to this time. In cases where a Class I railroad makes the investment to bring an existing locomotive into compliance, it will almost certainly retain it for a period equivalent to two full useful life periods. Thus, they are not likely to sell any locomotives that they have brought into compliance until at least 12 years after they were originally brought into compliance.

Results

The results of the Class II and III emission analysis are summarized in Table 6-4. More detailed results are shown in Appendix I. These results show that NOx emissions from small railroads represent only about 6 percent of all locomotive emissions. These emissions will decrease slowly because of a fairly slow fleet turnover rate to Tier 0 technology. The analysis projects no significant reductions in HC and PM emissions because Tier 2 locomotives are not expected to be phased into Class II and III fleets in large numbers in the foreseeable future.

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[84] "Locomotive Data for Small Railroads," Memorandum, Charles Moulis, U.S. EPA, to public docket A-94-31, December 5, 1997.

Table 6-4

Results of Class II and III Emission Analysis

	Emission (Metric Tons/Year)			Reductions (Metric Tons/Year)			Percent Reduction		
Year	HC	NOx	PM	HC	NOx	PM	HC	NOx	PM
1999	2,150	58,100	1,430	0	0	0	0%	0%	0%
2000	2,150	58,100	1,430	0	0	0	0%	0%	0%
2005	2,150	57,200	1,430	0	900	0	0%	2%	0%
2010	2,150	56,000	1,430	0	2,100	0	0%	4%	0%
2015	2,150	52,900	1,430	0	5,200	0	0%	9%	0%
2020	2,150	49,400	1,430	0	8,800	0	0%	15%	0%
2025	2,150	45,800	1,430	0	12,300	0	0%	21%	0%
2030	2,150	42,300	1,430	0	15,900	0	0%	27%	0%
2035	2,150	38,700	1,430	0	19,400	0	0%	33%	0%
2040	2,150	38,200	1,430	0	19,900	0	0%	34%	0%

6.4 Passenger Railroad Analysis

Assumptions

According to the American Public Transit Association (APTA) there were approximately 463 diesel locomotives in commuter rail service in 1995, with 397 of these locomotives originally manufactured after 1972. These 463 locomotives consumed about 61 million gallons of diesel fuel that year.[85] In addition, Amtrak currently has 315 diesel locomotives in service, consuming about 72 million gallons of diesel fuel per year. EPA is projecting that 100 locomotives will be brought into compliance during each of the first five years of the program, and that all uncontrolled locomotives will be removed from passenger service by 2011. Sales of freshly manufactured passenger locomotives are assumed to be 30 new units per year. Average passenger locomotive emission rates are assumed to be the same as the average emission rates for Class I line-haul locomotives.

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[85] "1996 Transit Vehicle Fact Book", American Public Transit Association.

Results

The results of the passenger locomotive emission analysis are summarized in Table 6-5. More detailed results are shown in Appendix I. These results show that a 39 percent reduction in NOx emissions is expected by 2010. Significant reductions in HC and PM emissions are not expected until Tier 2 locomotives are phased into the fleet in large numbers. The rate of phase-in is expected to be roughly similar to the rate for Class I freight service.

Table 6-5

Results of Passenger Emission Analysis[86]

	Emission (Metric Tons/Year)			Reductions (Metric Tons/Year)			Percent Reduction		
Year	HC	NOx	PM	HC	NOx	PM	HC	NOx	PM
1999	1,330	36,000	890	0	0	0	0%	0%	0%
2000	1,330	36,000	890	0	0	0	0%	0%	0%
2005	1,300	26,700	870	30	9,200	20	2%	26%	2%
2010	1,180	20,900	780	150	15,100	100	11%	42%	12%
2015	1,060	18,800	700	270	17,100	190	20%	48%	21%
2020	940	16,900	610	390	19,100	270	29%	53%	31%
2025	820	15,000	530	510	21,000	360	38%	58%	40%
2030	710	13,700	440	620	22,300	440	47%	62%	50%
2035	710	13,700	440	620	22,300	440	47%	62%	50%
2040	710	13,700	440	620	22,300	440	47%	62%	50%

6.5 Summary of Environmental Benefits

Estimated emissions and emission reductions for the total U.S. locomotive fleet are shown in Table 6-6 and Figure 6-2. The totals are dominated by the emissions and reductions from Class I freight locomotives, which represent about 90 percent of all current emissions from locomotives. The marginal benefits of each tier of standards, which are used in Chapter 7 to calculate marginal cost-effectiveness, are shown in Appendix I.

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[86] The results shown in this table are the same as those found in the December 1997 version of this document. Results of corrected analyses are contained in Appendix O.

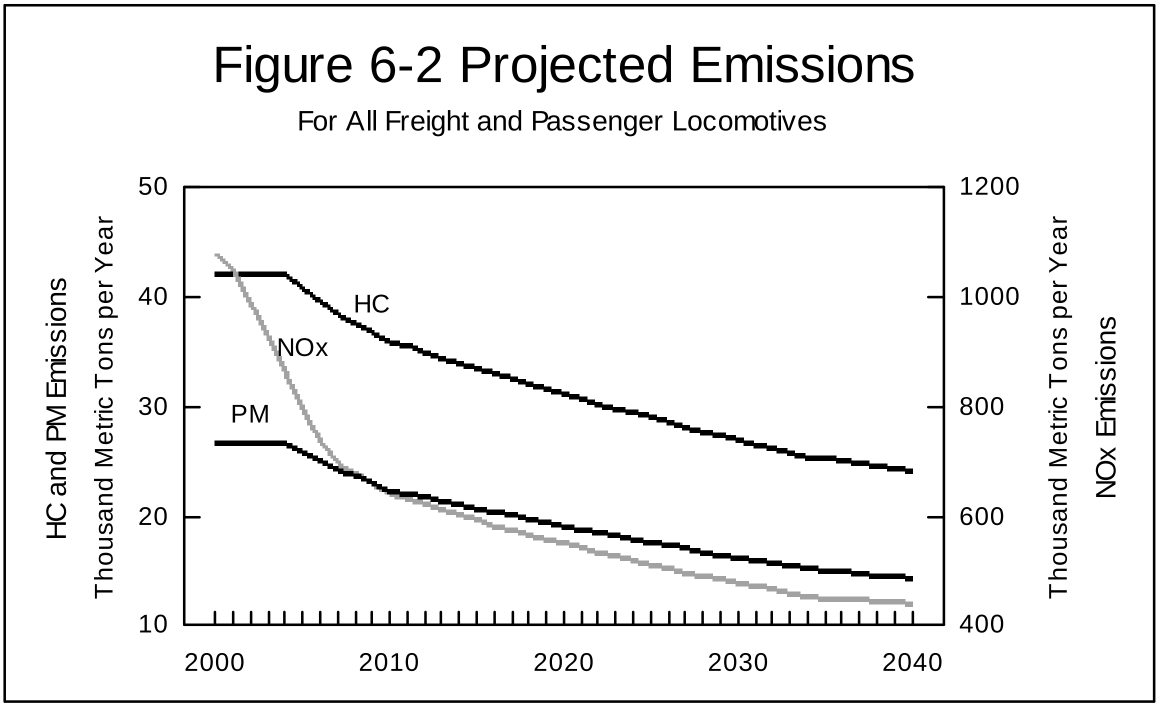

Figure 6-2 Projected Emissions

For All Freight and Passenger Locomotives

It is important to note that the NOx reductions discussed previously will also reduce ambient PM concentrations. This is because oxides of nitrogen react in the atmosphere to form nitrate particulate matter. It has been estimated that the reduction in nitrate particulate matter that would result from a 100 ton NOx reduction would be roughly equivalent to a four ton reduction in direct particulate matter.[87] Thus, given the NOx and direct PM reductions shown in Table 6-6, EPA believes that the secondary particulate reductions resulting from these regulations will be greater than the direct particulate reductions. For example, in 2020, EPA estimates that these regulations will result in a NOx reduction of over 530,000 metric tons per year, which would be equivalent to a PM reduction of more than 21,000 tons per year if the estimated four percent conversion rate is accurate. This is three times the amount of direct PM reduction resulting from the regulations in that same year.

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[87] "Benefits of Mobile Source NOx Related Particulate Matter Reductions", Final Report, October 1996, Systems Applications International. Docket item #A-95-27-IV-A-01.

Table 6-6

Results of Emission Analysis for All Locomotives

	Emission (Metric Tons/Year)			Reductions (Metric Tons/Year)			Percent Reduction		
Year	HC	NOx	PM	HC	NOx	PM	HC	NOx	PM
1999	42,400	1,093,000	27,000	0	0	0	0%	0%	0%
2000	42,400	1,081,000	27,000	0	11,000	0	0%	1%	0%
2005	41,000	789,000	26,000	1,400	304,000	900	3%	28%	3%
2010	36,100	644,000	22,600	6,300	449,000	4,400	15%	41%	16%
2015	33,700	596,000	20,900	8,700	496,000	6,000	21%	45%	22%
2020	31,400	554,000	19,300	11,000	538,000	7,600	26%	49%	28%
2025	29,200	516,000	17,800	13,200	576,000	9,100	31%	53%	34%
2030	27,100	483,000	16,400	15,300	610,000	10,500	36%	56%	39%
2035	25,400	456,000	15,300	17,000	637,000	11,700	40%	58%	43%
2040	24,300	445,000	14,600	18,100	648,000	12,400	43%	59%	46%
Total Reductions (2000-2040)				417,000	20,100,000	288,000			

7.0 Costs and Cost-effectiveness

Background

EPA estimated the costs of compliance with the proposed standards in the Draft RSD, based in part on materials supplied by locomotive manufacturers and the railroad industry. After the proposal, EPA contracted with ICF, Incorporated, with its subcontractors, Acurex Environmental Corporation and Engine, Fuel, and Emissions Engineering, Incorporated (EF&EE), to update the economic analysis, based on the estimated costs for the most likely compliance technologies.[88] In most instances, the results of the cost study tended to confirm the EPA estimates, including the cost-effectiveness estimates. The current estimated compliance costs are based largely on the contractor studies, although some differences exist as a result of public comments received or other information available to EPA. Such differences from the Draft RSD and the contractor cost study will be noted where present. As a result of such differences, EPA is presenting a range of costs in several areas. In general, the cost estimates presented here tend to be somewhat conservative; that is, for those costs with significant uncertainty, EPA used the higher end of the estimated range.

Incremental compliance costs are presented for Tier 0, Tier 1 and Tier 2 locomotives on a total and per-locomotive basis. This incremental approach is appropriate because EPA believes that the technology will be applied sequentially, as the standards become more stringent. Locomotive cost components consist of initial equipment costs, and operating costs. The equipment costs consist of fixed costs and variable costs for the necessary hardware, which, when adjusted to include the manufacturer's markup for overhead and profit, comprise the initial cost increase to the operator. Fixed costs include engineering costs for compliance technology development; testing costs for development, certification, production line testing (PLT) and in-use testing; tooling costs to enable production of the hardware for compliance; and technical support costs for training and technical support publications to be used by personnel operating and maintaining the locomotives. Operating costs include incremental fuel costs, (incremental to those that would be incurred without the compliance technology) and incremental maintenance costs, including remanufacturing costs.

A breakdown of the testing costs used in calculating fixed costs is presented in Table 7-1, while the total fixed costs, including testing costs, are shown in the per-locomotive costs calculated in Tables 7-2A (base case) and 7-2B (high range). This latter table is included as a sensitivity analysis to show the effects of modifying base case assumptions regarding development costs, testing costs and operating costs (which

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[88] "Cost Estimates for Meeting the Proposed Locomotive Emission Standards", Engine, Fuel, and Emission Engineering, Inc., September, 1997; and "Locomotive Technologies to Meet SOP (sic) Emission Standards", Acurex Environmental Corp., August, 1997.

are detailed below). Tables 7-2A and 7-2B also include the estimated locomotive populations used in allocating the fixed costs. The model categories listed in these tables, (e.g., "Tier 0 - A" or "Tier 2 - B") represent different locomotive model types, consistent with the descriptions of Chapters 3 and 4. Where applicable, costs are presented in actual and discounted format.[89]

7.1 Initial Cost Increase for Locomotives

The initial cost increase for locomotives (sometimes known as the first price increase (FPI)) consists of the fixed costs to the manufacturer for such things as investment capital, research and development, etc. and the variable costs, which are the costs for the necessary emission control hardware on each individual locomotive. Variable costs vary with production, while fixed costs are allocated to whatever production level is realized.

7.1.1 Fixed Costs

Fixed costs are those that represent the initial investments that must be made by the manufacturer before the beginning of production. These will vary in magnitude with the emission standard (Tier 0, Tier 1, Tier 2) for which compliance is required, and with the amount of emission control required by individual manufacturers for their product lines, but will tend to fall into the same general categories (e.g., engineering costs or technical support costs). It is important to note that the fixed costs necessary to develop Tier 0 certification kits apply independently to each remanufacturer developing a kit. Thus, if three different remanufacturers independently develop a kit for the same model of locomotive, then the fixed cost component for that locomotive model would be three times what it be if only one remanufacturer developed a kit. The numbers of suppliers assumed for each model category of Tier 0 locomotive in this analysis are shown in Tables 7-2A and 7-2B. These numbers are EPA's projection that are based on the current numbers of independent part suppliers and remanufacturers for the various locomotive models. EPA assumed that many current suppliers and remanufacturers will seek to avoid the need to certify by making business arrangements with other businesses that are certifying. Thus, the number of suppliers assumed for each kit is less than the total number of suppliers.

Because the fixed costs are for goods and services that are useful for more than one year of production, it is appropriate to amortize or allocate these costs over more than one year of production. In its rulemakings, EPA normally assumes that the manufacturers would recover their development costs within the first five years of production. For Tier 2, this becomes important because the standards are effective for a considerable length of time. The Tier 2 development costs were therefore assumed to be recovered by 2010, and a separate reduced fixed cost component was used in the

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[89] Discounted costs represent the net present value of costs.

lifetime benefit calculation after that year. After 2010 fixed costs were limited to testing costs for PLT and in-use testing. For Tier 1, the effective period for allocation of development work is shorter, more on the order of three years. The period of compliance for Tier 0 is longer, due to the long useful life and staggered remanufacture schedule of most Tier 0 locomotives, so a period of five years can be used. It is not necessary to calculate separate compliance costs reflecting fully-recovered fixed costs for Tiers 0 and 1 since the initial hardware costs occur only at original manufacture (for Tier 1) or the first remanufacture (for Tier 0), and thus are applicable only during the first few years of the program. This does not materially affect the cost-effectiveness of the standards, and any minor error involved would be on the side of conservatism in cost determination. Fixed costs are normally also allocated on a per-locomotive basis according to the number of units produced. Such costs include developmental engineering and testing costs (the latter including facility, equipment and operating costs), as well as tooling and technical support costs as described above.

TABLE 7-1

TESTING COSTS

		Number	Unit Cost	Total Cost	Annual Cost
Capital Costs[a]	Test Systems	6	$340,000	$2,040,000	
	Auxiliary Equipment	4	$185,000	$740,000	
	Equipment Subtotal			$2,780,000	$395,809
	Facility Costs	4	$2,000,000	$8,000,000	$1,139,020
	TOTAL CAPITAL			$10,780,000	**$1,534,829**
Operating Costs	Technicians	12	$70,000		$840,000
	Engineers	4	$100,000		$400,000
	Maintenance	6	$30,000		$180,000
	Subtotal				$1,420,000
	Overhead				$213,000
	TOTAL OPERATING				**$1,633,000**
TOTAL COSTS					**$3,167,829**

	2000-2010	After 2010[a]
Number of Tests/Year	200	50
Allocated Cost/Test	$15,839	$32,660
Consumables	$5,000	$5,000
Lost Service[b]	$300	$1,200
Cost/Test	$21,139	$38,860

[a] Capital costs assumed to be recovered by 2010.

[b] Average cost for lost service time varies because of different mix of development, certification, production line and in-use testing.

TABLE 7-2A PER-LOCOMOTIVE COSTS

										2005 - 2010		After 2010	
BASE CASE													
Standards	**Tier 0**	**Tier 0**	**Tier 0**	**Tier 0**	**Tier 0**	**Tier 1**	**Tier 1**	**Tier 1**	**Tier 1**	**Tier 2**	**Tier 2**	**Tier 2**	**Tier 2**
Model Category	A	B	C	D	E	A	B	C	D	A	B	A	B
NUMBER OF LOCOMOTIVES	3000	4900	2930	2035	2965	360	360	360	360	1700	1700	300	300
VARIABLE COSTS:													
2 deg timing retard	X	X	X	X	X	X	X	X	X				
4 deg timing retard	X	X								X	X	X	X
4 pass aftercooler	–	$5,000	$5,000	$5,000	–	–	–	–	–	–	–	–	–
Improved mechanical injectors	–	$800	–	–	–	–	–	–	–	–	–	–	–
Add electronic fuel injection	–	–	–	$35,000	–	–	–	–	–	–	–	–	–
Improved electronic injectors	–	–	$2,000	–	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000
Increased compression ratio	–	–	–	–	$800	$800	$800	–	–	–	–	–	–
Improved turbocharger	–	–	–	$25,000	$25,000		$25,000	–	–	–	–	–	–
Split cooling	–	–	–	–	–	$25,000		$25,000	$25,000	$25,000	$25,000	$25,000	$25,000
High pressure injection	–	–	–	–	–	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000
Combustion chamber design	–	–	–	–	–	$800	$800	$800	$800	$800	$800	$800	$800
Assembly costs	$0	$4,480	$6,720	$4,480	$6,720	$6,720	$6,720	$560	$560	$560	$560	$560	$560
TOTAL VARIABLE COSTS	**$0**	**$10,280**	**$13,720**	**$69,480**	**$34,520**	**$37,320**	**$37,320**	**$30,360**	**$30,360**	**$30,360**	**$30,360**	**$30,360**	**$30,360**
FIXED COSTS:													
Number of tests	20	20	40	20	40	200	200	200	200	400	400	15	15
Engineering costs	$800,000	$1,700,000	$2,800,000	$1,700,000	$2,800,000	$3,600,000	$3,600,000	$3,600,000	$3,600,000	$4,000,000	$4,000,000	–	–
Testing costs	$422,783	$422,783	$845,566	$422,783	$845,566	$4,227,829	$4,227,829	$4,227,829	$4,227,829	$8,455,659	$8,455,659	$582,900	$582,900
Tooling	–	–	–	–	–	$1,000,000	$1,000,000	$1,000,000	$1,000,000	$1,000,000	$1,000,000	–	–
Technical Support	$200,000	$350,000	$500,000	$350,000	$500,000	$500,000	$500,000	$350,000	$350,000	$350,000	$350,000	–	–
Fixed Costs/Supplier	$1,422,783	$2,472,783	$4,145,566	$2,472,783	$4,145,566	$9,327,829	$9,327,829	$9,177,829	$9,177,829	$13,805,659	$13,805,659	$582,900	$582,900
TOTAL FIXED COSTS	**$4,268,409**	**$7,418,409**	**$12,436,818**	**$2,472,803**	**$4,145,606**	**$9,328,029**	**$9,328,029**	**$9,178,029**	**$9,178,029**	**$13,806,059**	**$13,806,059**	**$582,915**	**$582,915**
Cost per Locomotive	**$1,423**	**$1,514**	**$4,245**	**$1,215**	**$1,398**	**$25,911**	**$25,911**	**$25,495**	**$25,495**	**$8,121**	**$8,121**	**$1,943**	**$1,943**
Number of suppliers	3	3	3	1	1	1	1	1	1	1	1	1	1
TOTAL MFG COSTS:	**$1,707**	**$14,153**	**$21,558**	**$84,834**	**$43,102**	**$75,877**	**$75,877**	**$67,025**	**$67,025**	**$46,177**	**$46,177**	**$38,764**	**$38,764**
(Includes 20% Mfr. markup)													
OPERATING COSTS:													
FUEL COST:													
Average Fuel Consumption	104000	104000	297000	104000	297000	297000	297000	350000	350000	350000	350000	350000	350000
FE Penalty	2%	1%	1%	1%	2%	1%	1%	1%	1%	2%	2%	2%	2%
Gallons of fuel/year	2,080	1,040	2,970	1,040	5,940	2,970	2,970	3,500	3,500	7,000	7,000	7,000	7,000
Cost per year (@ $0.70/Gal.)	$1,456	$728	$2,079	$728	$4,158	$2,079	$2,079	$2,450	$2,450	$4,900	$4,900	$4,900	$4,900
TOTAL FUEL COST	**$21,840**	**$10,920**	**$43,659**	**$10,920**	**$87,318**	**$83,160**	**$83,160**	**$98,000**	**$98,000**	**$196,000**	**$196,000**	**$196,000**	**$196,000**
INCREMENTAL MAINT.													
Cost per year	$0	$400	$846	$400	$846	$1,000	$1,000	$240	$240	$240	$240	$240	$240
Service life	15	15	21	15	21	40	40	40	40	40	40	40	40
TOTAL MAINT. COST	**$0**	**$6,000**	**$17,766**	**$6,000**	**$17,766**	**$40,000**	**$40,000**	**$9,600**	**$9,600**	**$9,600**	**$9,600**	**$9,600**	**$9,600**
TOTAL OPERATING COSTS:	**$21,840**	**$16,920**	**$61,425**	**$16,920**	**$105,084**	**$123,160**	**$123,160**	**$107,600**	**$107,600**	**$205,600**	**$205,600**	**$205,600**	**$205,600**
PRESENT VALUE	$13,261.12	$10,273.73	$31,693.92	$10,273.73	$54,220.98	$41,048.33	$41,048.33	$35,862.30	$35,862.30	$68,524.98	$68,524.98	$68,524.98	$68,524.98
TOTAL COST TO RR	**$23,547.36**	**$31,072.75**	**$82,982.58**	**$101,754.16**	**$148,185.82**	**$199,037.43**	**$199,037.43**	**$174,625.43**	**$174,625.43**	**$251,777.45**	**$251,777.45**	**$244,363.66**	**$244,363.66**
NPV COST TO RR	$14,968.49	$24,426.48	$53,251.49	$95,107.89	$97,322.80	$116,925.76	$116,925.76	$102,887.73	$102,887.73	$114,702.44	$114,702.44	$107,288.64	$107,288.64

TABLE 7-2B PER-LOCOMOTIVE COSTS

HIGH CASE										2005 - 2010		After 2010	
Standards	**Tier 0**	**Tier 0**	**Tier 0**	**Tier 0**	**Tier 0**	**Tier 1**	**Tier 1**	**Tier 1**	**Tier 1**	**Tier 2**	**Tier 2**	**Tier 2**	**Tier 2**
Model Category	A	B	C	D	E	A	B	C	D	A	B	A	B
NUMBER OF LOCOMOTIVES	3000	4900	2930	2035	2965	300	300	300	300	1500	1500	300	300
VARIABLE COSTS:													
2 deg timing retard	X	X	X	X	X	X	X	X	X				
4 deg timing retard	X	X								X	X	X	X
4 pass aftercooler	–	$5,000	$5,000	$5,000	–	–	–	–	–	–	–	–	–
Improved mechanical injectors	–	$800	–	–	–	–	–	–	–	–	–	–	–
Add electronic fuel injection	–	–	–	$35,000	–	–	–	–	–	–	–	–	–
Improved electronic injectors	–	–	$2,000	–	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000
Increased compression ratio	–	–	–	–	$800	$800	$800	–	–	–	–	–	–
Improved turbocharger	–	–	–	$25,000	$25,000		$25,000	–	–	–	–	–	–
Split cooling	–	–	–	–	–	$25,000		$25,000	$25,000	$25,000	$25,000	$25,000	$25,000
High pressure injection	–	–	–	–	–	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000
Combustion chamber design	–	–	–	–	–	$800	$800	$800	$800	$800	$800	$800	$800
Assembly costs	$0	$4,480	$6,720	$4,480	$6,720	$6,720	$6,720	$560	$560	$560	$560	$560	$560
TOTAL VARIABLE COSTS	**$0**	**$10,280**	**$13,720**	**$69,480**	**$34,520**	**$37,320**	**$37,320**	**$30,360**	**$30,360**	**$30,360**	**$30,360**	**$30,360**	**$30,360**
FIXED COSTS:													
Number of tests	20	20	40	20	40	200	200	200	200	400	400	15	15
Engineering costs	$1,200,000	$2,550,000	$4,200,000	$2,550,000	$4,200,000	$5,400,000	$5,400,000	$5,400,000	$5,400,000	$6,000,000	$6,000,000	–	–
Testing costs	$634,174	$634,174	$1,268,349	$634,174	$1,268,349	$6,341,744	$6,341,744	$6,341,744	$6,341,744	$12,683,488	$12,683,488	$874,350	$874,350
Tooling	–	–	–	–	–	$1,000,000	$1,000,000	$1,000,000	$1,000,000	$1,000,000	$1,000,000	–	–
Technical Support	$200,000	$350,000	$500,000	$350,000	$500,000	$500,000	$500,000	$350,000	$350,000	$350,000	$350,000	–	–
Fixed Costs/Supplier	$2,034,174	$3,534,174	$5,968,349	$3,534,174	$5,968,349	$13,241,744	$13,241,744	$13,091,744	$13,091,744	$20,033,488	$20,033,488	$874,350	$874,350
TOTAL FIXED COSTS	**$8,136,778**	**$14,136,778**	**$23,873,555**	**$3,534,194**	**$5,968,389**	**$13,241,944**	**$13,241,944**	**$13,091,944**	**$13,091,944**	**$20,033,888**	**$20,033,888**	**$874,365**	**$874,365**
Cost per Locomotive	**$2,712**	**$2,885**	**$8,148**	**$1,737**	**$2,013**	**$44,140**	**$44,140**	**$43,640**	**$43,640**	**$13,356**	**$13,356**	**$2,915**	**$2,915**
Number of suppliers	4	4	4	1	1	1	1	1	1	1	1	1	1
TOTAL MFG COSTS: (Includes 20% Mfr. markup)	**$3,255**	**$15,798**	**$26,242**	**$85,460**	**$43,840**	**$97,752**	**$97,752**	**$88,800**	**$88,800**	**$52,459**	**$52,459**	**$39,929**	**$39,929**
OPERATING COSTS:													
FUEL COST:													
Average Fuel Consumption	104000	104000	297000	104000	297000	297000	297000	350000	350000	350000	350000	350000	350000
FE Penalty	4%	2%	2%	2%	4%	2%	2%	2%	2%	4%	4%	4%	4%
Gallons of fuel/year	4,160	2,080	5,940	2,080	11,880	5,940	5,940	7,000	7,000	14,000	14,000	14,000	14,000
Cost per year (@ $0.70/Gal.)	$2,912	$1,456	$4,158	$1,456	$8,316	$4,158	$4,158	$4,900	$4,900	$9,800	$9,800	$9,800	$9,800
TOTAL FUEL COST	**$43,680**	**$21,840**	**$87,318**	**$21,840**	**$174,636**	**$166,320**	**$166,320**	**$196,000**	**$196,000**	**$392,000**	**$392,000**	**$392,000**	**$392,000**
INCREMENTAL MAINT.													
Cost per year	$0	$400	$846	$400	$846	$1,000	$1,000	$240	$240	$240	$240	$240	$240
Service life	15	15	21	15	21	40	40	40	40	40	40	40	40
TOTAL MAINT. COST	**$0**	**$6,000**	**$17,766**	**$6,000**	**$17,766**	**$40,000**	**$40,000**	**$9,600**	**$9,600**	**$9,600**	**$9,600**	**$9,600**	**$9,600**
TOTAL OPERATING COSTS:	**$43,680**	**$27,840**	**$105,084**	**$27,840**	**$192,402**	**$206,320**	**$206,320**	**$205,600**	**$205,600**	**$401,600**	**$401,600**	**$401,600**	**$401,600**
PRESENT VALUE	$26,522	$16,904	$54,221	$16,904	$99,275	$68,765	$68,765	$68,525	$68,525	$133,850	$133,850	$133,850	$133,850
TOTAL COST TO RR	**$46,935**	**$43,638**	**$131,326**	**$113,300**	**$236,242**	**$304,072**	**$304,072**	**$294,400**	**$294,400**	**$454,059**	**$454,059**	**$441,529**	**$441,529**
NPV COST TO RR	$29,777	$32,702	$80,463	$102,364	$143,115	$166,517	$166,517	$157,325	$157,325	$186,309	$186,309	$173,780	$173,780

Testing Costs

Testing costs include developmental testing, as well as certification testing, production line testing and in-use testing. Developmental testing, which represents the largest segment of the projected testing costs, is necessary for developing and evaluating the necessary compliance strategies. The amount of developmental testing that is necessary is determined by each individual manufacturer or remanufacturer. Certification and PLT provide evidence of the manufacturer's initial compliance with the applicable emission standards, and in-use testing provides evidence of the continued durability of emission control systems. The amount of certification, PLT and in-use testing are specified by EPA.

Testing costs include the costs of any necessary additional facilities and equipment for emissions testing, plus engineering, operating and maintenance costs for the testing facility. A detailed breakdown of these costs may be found in the EF&EE contractor study, and they are summarized in Table 7-1. The contractor assumed that the major manufacturers and a limited number of aftermarket remanufacturers would need test equipment sufficient to equip six test cells, at a cost of $340,000 per cell, plus auxiliary facility equipment, such as calibration gas handling equipment, particulate weighing equipment, and a spur track for bringing locomotives to the test site, at an estimated cost of $185,000 per facility. EF&EE assumed one such auxiliary system could service two test cells, and that four such systems would be required, since the two major manufacturers would already have one test site and would develop one more each. The contractor allocated these costs over a ten year period.

The contractor assumed that although the two major manufacturers have existing test cells, each would require an additional test cell for Tier 0 testing at an estimated cost of $2 million per cell, but included these costs in the Tier 0 costs. EPA believes that these facilities will be used for Tier 1 and Tier 2 testing as well as for Tier 0. Therefore, the Agency has included the costs for two additional test cells for the major manufacturers and two for the independent remanufacturers in the calculation of the testing costs applicable for all tiers. EPA also received a number of comments regarding the lack of estimated test facility costs in the Draft RSD. The comments contained estimates ranging from $1 to 3 million. EPA believes that the cost study estimate of $2 million each for additional test facilities is reasonable and represents the mid-point of the range. Allocated facility costs are thus included along with allocated equipment costs in the cost per test calculation.

In addition to allocated equipment and facility costs, testing costs also include an operating cost component. In the cost study, EF&EE assumed that two technicians and a supervisory engineer would be required for each test cell (or group of two test cells in the case of the major manufacturers). The contractor also assumed costs for test system calibration and maintenance and for overhead at a rate of 15 percent of direct costs. EPA is assuming $5,000 per test for consumables (test fuel, reference gases, electrical power, etc.), which is intended to be conservative. Since a fraction of the tests will be for in-use testing, EPA also assumed a cost for removing the locomotive from service for testing. Although the Agency received comments placing this cost at up to 17 days lost time at a cost of $14,000, EPA will use the AAR estimate of 8 days lost time at a cost of $6,000, due to the considerable AAR member experience with FRA 92-day safety inspections. EPA estimates that in-use testing will represent about five percent of the total test load during the early years of the program when a great deal of development testing will be conducted, but will increase to approximately 20 percent of the total test load after 2010, when the developmental testing should be completed and the total testing load diminishes. These figures are also reflected in Table 7-1.

As can be seen from Table 7-1, these costs when allocated over the estimated testing requirement, amount to about $21,000 per test prior to 2010 and about $39,000 per test after 2010 when the developmental testing is completed. This differs from both EPA's original estimate of $10,000 per test and the estimate of $10,237 per test provided in the EF&EE cost study. However, as noted above, EPA has added allocated facility costs and allowances for consumables and lost locomotive service to the estimated costs, and has adjusted the cost-per-test calculation accordingly.

EPA also received a number of testing cost estimates in the public comments; the near-term estimates for the type of testing that will most likely be required tended to fall into the $20,000 to $30,000 range. The above-mentioned adjusted cost per test falls into the lower end of that range, so as a sensitivity analysis EPA assumed a high range cost per test of 1.5 times both of the costs listed in Table 7-1; the resulting testing costs will be used in calculating the high range cost and cost/benefit figures that are presented in Table 7-2B.

Engineering Costs

The engineering costs category represents the estimated average cost for the number of engineering work years projected to be required to develop the calibrations and hardware necessary for meeting the emission standards. This also includes the effort for any ancillary changes that must be made to the locomotives to accommodate the required new hardware. The engineering costs used in the current analysis were taken from the EF&EE cost study and are shown in Tables 7-2A (base case) and 7-2B (high range). In Table 7-2B the engineering costs were increased by a factor of 1.5 as a part of the sensitivity analysis.

Tooling Costs

Tooling costs are also shown in the fixed costs portion of Tables 7-2 A and 7-2B. These include costs for any additional or modified tooling necessary to produce the emission control hardware, as well as for any required setup changes. Because Tier

0 compliance is estimated to be achieved through calibration changes or through hardware obtained from suppliers (particularly in the case of aftermarket remanufacturers), no specific tooling costs were estimated for Tier 0. Tooling costs for Tier 0 parts were assumed to be included in the component costs to the remanufacturer. Tooling costs for the other tiers were taken from the cost study.

Technical Support

Technical support consists of any changes that would be required in the technical support that manufacturers provide to users. This would include any necessary operator or maintenance training and changes to technical publications that provide operating and maintenance guidance. These costs were not included in the Draft RSD, but were estimated in the EF&EE cost study, and are included in the current analysis. These costs are also included in the fixed costs portion of Tables 7-2A and 7-2B.

7.1.2. Variable Costs

Hardware

Hardware requirements for meeting the applicable emission standards will vary with the stringency of the standards, i.e., Tier 0, Tier 1, or Tier 2, and by manufacturer, according to the hardware changes required to meet the standards. These variations are outlined below and are discussed more fully in the Acurex technology study and the EF&EE cost study. In general, however, manufacturers will need to use some combination of fuel injection timing calibration; fuel injector, turbocharger, and/or charge air cooling improvements; and possibly combustion chamber or piston modifications. Particularly for Tier 0, different combinations of these strategies will be used for different locomotives. A listing of these strategies, along with their projected costs and estimated usage, is presented in Table 7-3. For example, it is projected that about 50 percent of Tier 0 locomotives will have timing retarded by 2 degrees, and the other 50 percent will have timing retarded by 4 degrees. Similarly, it is projected that 60 percent of Tier 0 locomotives will add 4-pass aftercoolers. Representative model combinations are shown in Tables 7-2A and 7-2B. No separate model cases are shown for passenger locomotives, since these are generally variations of similar line-haul locomotives and should thus incur similar costs (fixed as well as variable). However passenger locomotives are included in the total cost calculations since the costs should be similar to those for freight locomotives.

Assembly Costs

Assembly costs include the labor and overhead costs for retrofitting (in the case of Tier 0) or for initial installation of the new or improved hardware. These will also vary with the characteristics of individual locomotives and the type of hardware necessary for compliance with the applicable emission standards. These costs are included in the summary figures in Tables 7-2A and 7-2B, and are discussed more fully in the contractor cost study.

Table 7-3

Incremental Hardware Cost And Usage

Expected Technology	Cost per Locomotive	Percent of Locomotives Using Technology		
		Tier 0	Tier 1	Tier 2
2 deg timing retard	--	50%	100%	
4 deg timing retard	--	50%		100%
4 pass aftercooler	$5,000	60%		
Improved mechanical injectors	$800	30%		
Add electronic fuel injection	$35,000	13%		
Improved electronic injectors	$2,000	37%	100%	100%
Engine Modifications	$800	20%	50%	
Improved turbocharger	$25,000	30%	25%	
Split cooling	$25,000		75%	100%
High pressure injection	$2,000		100%	100%
Combustion chamber design	$800		100%	100%

7.1.3. Total Locomotive Cost Increase

The fixed and variable costs, together with a manufacturer markup for overhead and profit, comprise the total manufacturing costs which represent the initial cost increase, or FPI, to the operator. A conservative manufacturer markup of 20 percent was assumed, based on the amount normally used as a target figure in the automotive industry.[90] Although the actual markup for automobiles and trucks tends to vary with economic conditions and other factors, this target figure was used for locomotives for the sake of conservatism and in the absence of any data on the actual markups

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[90] "Cost Estimations for Emission Control Related Component/ System and Cost Methodology Description", LeRoy H. Lindgren, March, 1978 (EPA-460/3-78-002).

achieved in the locomotive industry. Given the competitive nature of the industry, EPA believes the actual markups are likely to be lower. The total manufacturing costs or FPI are shown in Tables 7-2A and 7-2B.

Tier 0 Locomotives

In calculating the estimated FPI for Tier 0 locomotives, EPA assumed that the locomotives could be grouped into 5 categories (or engine families): older and newer line-haul locomotives from the two major manufacturers, and switch locomotives from one manufacturer. This latter group was not included in the EF&EE cost study because the contractor did not feel it would be cost-effective to upgrade these locomotives. However, EPA believes a significant number will be certified, due to the relatively low cost involved. The EF&EE cost study estimated that it may be more cost-effective to improve the existing unit injectors of older locomotives, since they typically do not accumulate as many miles each year as the newer locomotives. However, based on comments received, EPA does not necessarily concur that this will be true for all such locomotives, and has included electronic injection systems for some of the older locomotives as well. The other major difference in costs results from the need for an improved turbocharger for locomotives with higher smoke emissions, which would not be required for locomotives which did not have this problem. Changes in injection timing calibrations would likely be used for all these scenarios.

Tier 1 Locomotives

The estimated initial cost increase for Tier 1 locomotives are shown in Tables 7-2A and 7-2B. The EF&EE cost study made the distinction between mechanical and electronic injection designs for Tier 1 locomotives. Fuel injection cost differences would thus arise from the fact that some current locomotives are already equipped with electronic injector systems, which would merely need to be upgraded, rather than replaced. EPA believes that all Tier 1 locomotives will have injection systems that are upgraded versions of the current electronic injectors. Therefore, the costs used in all calculations are based on the upgraded electronic injector scenario, rather than conversion from mechanical to electronic injection. Improved charge air cooling and limited in-cylinder modifications, e.g., for reduced oil consumption or higher compression ratio, as well as changes in injection timing calibrations, were also estimated to be required. EPA also believes that early versions of the new engine designs that will be used to meet the Tier 2 standards will make their appearance during the Tier 1 period. Thus, the tables show two Tier 1 models for each manufacturer.

Tier 2 Locomotives

The estimated initial cost increases for Tier 2 locomotives are shown in Tables 7-2A and 7-2B. Costs for Tier 2 compliance are based on new and improved engine designs already under development by the two major manufacturers. The existence of these designs, plus the 7 years of lead time available for development should result in cleaner engines that are able to meet the Tier 2 standards with minimum incremental costs over the developmental costs that would otherwise have been incurred for development of the uncontrolled engines. Again, the basic strategies likely to be used are injection timing calibrations, low-temperature charge air coolers and fuel injection improvements, largely the addition of rate shaping capability in the latter case. The Acurex report projected a possible need for EGR for some Tier 2 locomotives, however, EF&EE and EPA did not include EGR in the projected compliance strategies. EPA believes that if EGR were to be used at all, it would only be used on the lower power notches. It is also important to note that since the manufacturers are expected to introduce early versions of these new models during the Tier 1 time period, some of the emission control development cost is assigned to the Tier 1 locomotives. Compliance with the Tier 2 standards will actually be a continuation of the Tier 1 development process.

7.2. Incremental Operating Cost Increases

The incremental operating costs include any increase or decrease in the amount of fuel consumed as a result of the new standards, plus any incremental maintenance costs. This latter category would include maintenance on any new hardware required or additional maintenance on existing hardware. Any incremental subsequent remanufacture costs would also be included in the total. These costs are shown in the operating cost sections of Tables 7-2A and 7-2B.

7.2.1. Incremental Fuel Cost

EPA estimated the fuel economy ramifications of various emission control technologies in the Draft RSD. Public comments on the subject were also received, and incremental fuel costs (or savings) were also presented for the strategies considered in the contractor cost study. These are expressed in terms of percent increases or decreases from current levels. However, estimates for current fuel consumption levels show considerable variation.

In the Draft RSD, EPA calculated an annual per-locomotive cost of a one percent decrease/increase in fuel economy by multiplying the cost of fuel used by Class I railroads in 1992, $1,913,000,000, by a one percent fuel economy penalty/benefit and divided by the number of locomotives in use during 1992, rounded to the nearest thousand (i.e. approximately 18,000 locomotives). In terms of gallons of fuel consumed (at $0.63 per gallon), this represents roughly 167,900 gallons. Total fuel economy penalties/benefits of one percent from pre-regulated baseline levels would thus result in a calculated annual per-locomotive cost or benefit of $1,062.

On the other hand, in the contractor cost study, EF&EE assumed total per locomotive fuel consumption rates of 104,000 and 297,000 gallons per year, depending on application (i.e., light or heavy usage). EF&EE assumed a fuel consumption rate of 445,000 gallons per year for the advanced technology engines projected to be used for Tier 2 compliance. However, in their comments on the NPRM, EMD projected a fuel consumption rate of 350,000 gallons per year for their new 6,000hp locomotives. Since the OEM has developmental data for their products and should thus be in a better position to make fuel consumption estimates for their new technology, EPA will use this estimate for Tier 2, along with the Tier 0 and Tier 1 estimates from the cost study. The fuel consumption rates assumed are shown in the operating costs section of Tables 7-2A and 7-2B. These fuel rates, however, are only used for these per locomotive calculations; total costs were calculated from total fuel consumption estimates provided by the railroads.

As stated above, EPA received comments concerning projected fuel economy penalties. Some of these comments projected penalties as high as 5-10 percent, however this latter estimate appears to assume use of EGR on all models for meeting the Tier 2 standards. As stated above, EPA does not believe this will be required, and has projected fuel economy penalties of two percent as its best estimate of the Tier 2 fuel economy effects of the current rulemaking. Based on past developments in the industry, EPA further believes that manufacturers will make every effort to eliminate any initial fuel consumption penalties, and will have largely succeeded by 2010. However, projecting the necessary developmental costs involved and resulting fuel consumption levels is difficult at this time. Thus, for the sake of conservatism, the two percent projected fuel economy penalty will be retained in the analysis for the full 41 years covered by the analysis.

EPA also projected fuel economy penalties of 1-2 percent for Tier 0 locomotives, depending on other modifications that could serve to mitigate any fuel economy decrease involved. However, some Tier 0 locomotive models converting from mechanical to electronic fuel injection may actually see a decrease in fuel consumption. For Tier 1, EPA has assumed a one percent penalty, since the additional lead time afforded for meeting Tier 1 standards should allow additional development for the manufacturers to address any more negative fuel consumption effects. Nevertheless, as a sensitivity analysis, the Agency has also included a scenario which doubles the base-case incremental fuel consumption estimates. These are in the high range cost estimates presented in Table 7-2B and the high-range cost-effectiveness analysis shown in Table 7-5.

7.2.2. Incremental Maintenance

Routine Maintenance

EPA did not estimate any incremental maintenance costs in the Draft RSD. However, comments submitted by EMD stated that additional cost would be incurred for periodic replacement of electronic fuel injectors (which are routinely replaced at periodic intervals between remanufactures), and electronic injection wiring harnesses (which would also require replacement outside the normal remanufacture cycle due to embrittlement of the insulation from the heat generated by the engine). EF&EE agreed in its cost study that these would be legitimate costs, and provided estimated incremental costs for their replacement. EPA is including the cost of these replacements in the estimated maintenance costs for Tier 0 and Tier 1 locomotives, and the cost of improved injector replacement for Tier 2 locomotives. In addition, the contractor projected a small additional cost for routine periodic replacement of improved unit injectors, based on the difference in cost between the standard and improved versions. EPA has included the incremental costs for Tier 0 mechanical injector replacement in the maintenance costs. All of these periodic costs are converted to an average annual component and are included in the incremental maintenance costs shown in the operating costs section of Tables 7-2A and 7-2B. For purposes of this analysis, Tier 0 locomotives were assumed to have an average remaining service life at the time of remanufacture of 15 and 21 years, respectively, for older and newer locomotives, as shown in Tables 7-2A and 7-2B.

Subsequent Remanufactures

In addition to the initial equipment costs at time of original manufacture, and incremental maintenance costs for components that were upgraded at the time of manufacture/initial remanufacture, there will be some increase in costs at the time of each subsequent remanufacture of the locomotives. These costs are the incremental price increases in equipment that is routinely replaced at time of remanufacture. These costs are increased due to the improved parts necessary to meet the applicable emission standards. These costs are also included in the incremental maintenance costs presented in Table 7-3, and are discussed in greater detail in the EF&EE cost study.

7.2.3. Total Cost Increase

The estimated increased fuel costs and maintenance costs are included in the incremental operating costs for Tier 0, Tier 1 and Tier 2 locomotives shown in Tables 7-2A and 7-2B. These operating costs are presented as annual incremental costs and lifetime incremental costs for the estimated service life of the locomotive, in both actual and net present value (NPV) form. These operating costs are added to the first price increase to yield the lifetime costs per locomotive presented in the table. As discussed above, EPA has based its analysis on public comments received and on engineering judgement, as well as on the contractor study. Again, since there was considerable variation in the estimated fuel consumption figures contained in the comments and other sources, the incremental fuel consumption estimates from the base-case analysis were doubled to form a high-range estimate, which is used as a sensitivity analysis.

7.3. Total Program Costs and Cost-effectiveness

Tables 7-4 and 7-5 summarize the lifetime costs and emission benefits of the final locomotive rulemaking. While the costs presented are applicable for both NOx and PM reductions, the calculated benefits shown are for NOx only. However, it should be remembered that there are also significant emission reductions in PM (275,000 metric tons) and HC (400,000 metric tons). The costs are presented in an undiscounted (actual), and discounted (7% NPV) format. Costs and benefits were computed over a forty-one year program run to ensure complete fleet turnover, due to the extremely long service life of the typical locomotive. For the sake of consistency, total fuel consumption was calculated using the classwide fuel consumption rates used for calculation of the benefits in Chapter 6. Additional tables showing the year-by-year costs and emission benefits in both undiscounted and discounted form for the entire 41-year program can be found in Appendix F. Table F-1 shows undiscounted benefits and Table F-2 shows the benefits discounted at a rate of 7 percent.

The Draft RSD estimated the NOx cost-effectiveness for the program as a whole at $175 per metric ton. Based on the costs presented above and recomputed benefits, EPA has recalculated the cost-effectiveness for the total program at $163 per metric ton of NOx reduction for the base case (shown in Table 7-4) and $253 per metric ton for the high range case (shown in Table 7-5). As stated earlier, the high range case includes developmental engineering and testing costs at 150 percent of the base case and fuel consumption costs that are double the base case. Both of these sets of figures compare quite favorably to other NOx control strategies that have been adopted in recent years. For example, the cost-effectiveness for the large nonroad engines rulemaking was $160 to $360 per ton of NOx. The rule becomes even more cost-effective when the above-mentioned HC and PM benefits are considered.

EPA also calculated the marginal cost-effectiveness of the three tiers. The results of this calculation are shown in Appendix F, and are summarized in Table 7-6. To determine the marginal costs and benefits, EPA considered two additional scenarios: one in which the Tier 2 standards were eliminated so that the Tier 1 standards continued to apply after 2005; and one in which both the Tier 1 and Tier 2 standards were eliminated so that the Tier 0 standards continued to apply for the duration of the program. The total costs, NOx benefits and cost-effectiveness for these two scenarios are shown in the appendix. From these scenarios, EPA calculated the marginal cost-effectiveness for each of the three tiers of standards by dividing the marginal costs by the marginal benefits, as shown Table 7-6. The Tier 0 figures show the cost, benefits, and cost-effectiveness of continuing the Tier 0 standards for the full period 2000-2040. The Tier 1 figures show the marginal costs, benefits and cost-effectiveness associated with the Tier 1 standards, assuming that they were continued after 2005. The Tier 2 figures show the marginal costs, benefits and cost-effectiveness of the Tier 2 standards, which is calculated from the difference in costs and benefits between the total costs and benefits for all three tiers of standards (as shown in Table 7-4) and the previous scenario where the Tier 1 costs and benefits were continued from 2005-2040. As can be seen from the table, the costs for Tier 1 and Tier 2 are significantly higher than those for Tier 0. The differential would likely have been even greater if the costs were estimated over a shorter period of time. For example, when the cost-effectiveness is calculated for a 20 year period, rather than 41 years, the cost per ton for the total program increases by more than 40 percent, which could mean costs of upwards of $600 per ton at the high end of the cost range.

Table 7-4

Cost-Effectiveness Analysis: Base Case

Category	Total Costs
TIER 0	
Average number of Tier 0 locomotives produced per year (2000-2013)	1,214
Average number of Tier 0 locomotives in the fleet (2000-2040)	10,803
INCREMENTAL COSTS:	
Initial Manufacture	$470,446,480
Fuel consumption	$435,742,226
Maintenance	$217,159,792
TOTAL	$1,123,348,498
NPV	$584,926,672
TIER 1	
Average number of Tier1 locomotives produced per year (2002-2004)	480
Average number of Tier 1 locomotives in the fleet (2002-2040)	1,324
INCREMENTAL COSTS:	
Initial Manufacture	$102,890,062
Fuel consumption	$79,754,324
Maintenance	$32,013,080
TOTAL	$214,657,466
NPV	$132,572,277
TIER 2	
Average number of Tier 2 locomotives produced per year (2005-2040)	462
Average number of Tier 2 locomotives in the fleet (2005-2040)	9,078
INCREMENTAL COSTS:	
Initial Manufacture	$669,994,839
Fuel consumption	$1,186,615,407
Maintenance	$78,433,920
TOTAL	$1,935,044,166
NPV	$613,541,238
TOTAL COSTS	$3,273,050,130
NPV	$1,331,040,187
TOTAL NOx BENEFIT (Tons-M)	20,052,552
COST EFFECTIVENESS ($/Ton)	$163
NPV	$66

Table 7-5

Cost-Effectiveness Analysis: High Range

Category	Total Costs
TIER 0	
Average number of Tier 0 locomotives produced per year (2000-2013)	1,214
Average number of Tier 0 locomotives in the fleet (2000-2040)	10,803
INCREMENTAL COSTS:	
Initial Manufacture	$502,544,778
Fuel consumption	$871,484,452
Maintenance	$217,159,792
TOTAL	$1,591,189,022
NPV	$782,324,482
TIER 1	
Average number of Tier1 locomotives produced per year (2002-2004)	480
Average number of Tier 1 locomotives in the fleet (2002-2040)	1,324
INCREMENTAL COSTS:	
Initial Manufacture	$134,317,119
Fuel consumption	$159,508,649
Maintenance	$32,013,080
TOTAL	$325,838,848
NPV	$167,500,335
TIER 2	
Average number of Tier 2 locomotives produced per year (2005-2040)	462
Average number of Tier 2 locomotives in the fleet (2005-2040)	9,078
INCREMENTAL COSTS:	
Initial Manufacture	$706,878,325
Fuel consumption	$2,373,230,814
Maintenance	$78,433,920
TOTAL	$3,158,543,059
NPV	$951,097,583
TOTAL COSTS	$5,075,570,929
NPV	$1,900,922,399
TOTAL NOx BENEFIT (Tons-M)	20,052,552
COST EFFECTIVENESS ($/Ton)	$253
NPV	$95

Table 7-6

Marginal Cost-Effectiveness of Each Tier of Standards

Locomotive Standards	Base Case	High Range
TIER 0		
Total Costs	$2,422,421,411	$3,572,022,108
Total NOx Benefits	12,809,089	12,809,089
Cost-effectiveness ($/Ton)	$189	$279
TIER 1		
Marginal Costs	$850,628,719	$1,503,548,820
Marginal NOx Benefits	4,172,037	4,172,037
Cost-effectiveness ($/Ton)	$204	$360
TIER 2		
Marginal Costs	$618,662,877	$1,229,466,813
Marginal NOx Benefits	3,071,426	3,071,426
Cost-effectiveness ($/Ton)	$201	$400

APPENDICES

(Note: the appendices are contained in a separate document.)