EPA 460-3-91-001

Report to Congress

on

Railroad Emissions –
A Study Based On Existing Data

Prepared by

U. S. Environmental Protection Agency
Office of Air and Radiation
Office of Mobile Sources
Emission Control Technology Division
Standards Development and Support Branch

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1.0 INTRODUCTION

Section 404 of the Clean Air Act (CAA) Amendments of 1977* required the Environmental Protection Agency (EPA) to conduct a study of emissions of air pollutants from railroad locomotives and secondary rolling stock power sources with respect to: 1) their environmental impact, 2) methods for control, and 3) the status and effects of state regulations. The results of the study, together with recommendations on appropriate legislative action, were to be reported to the Congress.

This report presents the results of the study performed by the EPA for five selected Air Quality Control Regions and the recommendations based upon the findings of the study. Sections 6, 7, and 9 of this report address the three areas of study which were required by the legislation. Background information and computational procedures employed are provided in sections 4 and 5. Section 8 provides the estimates of costs and cost effectiveness associated with the methods which were considered for reducing railroad emissions.

Information on railroad emissions, state regulations, etc. was gathered by literature searches, questionnaires, interviews and from the Association of American Railroads (AAR) and locomotive manufacturers. This approach was selected as being the most timely as well as being the most cost-effective

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* "RAILROAD EMISSION STUDY

> Sec.404 (a) The Administrator of the Environmental Protection Agency shall conduct a study and investigation of emissions of air pollutants from railroad locomotives, locomotive engines, and secondary power sources on railroad rolling stock, in order to determine--
>
> (1) The extent to which such emissions affect air quality control regions throughout the United States,
>
> (2) The technological feasibility and the current state of technology for controlling such emissions, and
>
> (3) The status and effect of current and proposed state and local regulations affecting such emissions.
>
> (b) Within one-hundred and eighty days after commencing such study and investigation, the Administrator shall submit a report of such study and investigation, together with recommendations for appropriate legislation, to the Senate Committee on Environment and Public Works and the House Committee on Interstate and Foreign Commerce."

approach in terms of both personnel and financial resources. The literature searches, and AAR and manufacturer supplied data were utilized to estimate locomotive and secondary power source emissions levels, fleet size and distribution, usage patterns and duty cycles, and fuel consumption. Questionnaires were sent to state and local air pollution control agencies to survey their regulations, enforcement policies and problems and the perceived need for Federal regulations. Personnel of the Federal Railroad Administration and industry were interviewed.

Information gathered from the sources was compiled to develop the reported emissions inventories, air quality impacts, and effects of state and local regulations on interstate commerce.

Copies of the original draft of the report were provided, for review and comment, to the Association of American Railroads and to the locomotive manufacturers (Electromotive Division of General Motors (EMD) and General Electric (GE)). Comments and recommendations provided by the reviewers have, wherever possible, been incorporated into the report. Briefly, components of the report which were impacted by the reviewers recommendations and components where recommendations for change were made but not incorporated are as follows:

- Locomotive emissions data base sample size. Initially, the report had relied on a very small sample of data collected in 1972. Data collected from new locomotives and supplied by EMD in 1978 had not been used because of lack of information on the effects of locomotive aging on emissions. As a result of the review, AAR furnished data collected in 1984 from in-use locomotives. Provision of this data substantially increased the size of the data base. It also allowed another increase in the size of the data base by incorporation of the EMD data.

- Calculational procedures for estimating locomotive emissions. Originally, three methods were employed to calculate locomotive emissions. EPA recognized that two of the methods were very weak because of assumptions which had to be employed to utilize the available data. Because of concerns raised by the reviewers with respect to the veracity of the assumptions, two calculational methodologies were removed from the report.

- Number of locomotives in AQCRs. EMD expressed the opinion that the number of locomotives actually in operation in Air Quality Control Regions are lower than the numbers utilized in the report. EMD expressed the opinion that, for Chicago for example, the report overestimated the number of locomotives in use by a factor of 2.5. This area of the report was not changed because of lack of data to substantiate EMD's opinion. This comment should be borne in mind when reading the report, however, because the estimates of locomotive emissions in the AQCRs are directly proportional to the estimates of the number of locomotives in use in the AQCRs.

Emission control technology effects and costs. EMD recommended that the report present a generalized review of technological emission control approaches and the omission of quantitative values associated with control technology effects. EMD also expressed the opinion that reliable cost estimates could not be developed lacking better understanding of design changes associated with the application of control technologies.

While EPA shares the concerns raised by EMD, it is the opinion of EPA that sufficient information is available to allow the development of first order estimates of the effects and costs of control technologies. These sections of the report were, therefore, not changed as a result of the reviewers' comments.

2.0 SUMMARY OF CONCLUSIONS

Data available in the literature, for utilization in the performance of the railroad emissions estimates and especially for projections of emissions reductions achievable, were not extensive. The results of the study must, therefore, be viewed as providing indications with respect to the areas of probable concern and corrections thereof, rather than an exact determination of the impact of railroad emissions on the environment.

Conclusions resulting from the performance of this study are as follows:

1. State and local regulations exist in most localities for some control of locomotive emissions. The regulations and their enforcement are directed almost exclusively to visible emissions (smoke) with little if any attention to invisible gaseous emissions (i.e., HC, CO, and NOx). The regulations are directed to the steady-state operations of the locomotives with provisions for exceeding the standards under those conditions which are associated with short term and generally higher emission levels, e.g., during maintenance, after a cold start, after prolonged periods of idling and during accelerations.

2. There are relatively large differences in the stringencies of existing regulations. The stringencies of existing state and local regulations ranged between an opacity limit of 20 percent for the most stringent standard to an opacity limit of 60 percent for the least stringent standard. These differences do not appear to pose significant problems with respect to interstate commerce, possibly because of either weak enforcement of the regulations or because the railroads maintain separate fleets of locomotives for each region. There was insufficient data to either support or refute a third possibility, namely that the most stringent standard is easily achievable.

3. The stringency of enforcement of local regulations varies from locality to locality.

4. Transferral of locomotives with high smoke emissions from areas of strict enforcement to areas of either weak or no enforcement appears to be a practice used by railroads. There is not sufficient data to determine whether this practice results in large numbers of high-emitting locomotives being concentrated in some areas of the nation or whether as a result, railroad emissions in these areas are higher than would otherwise be predicted.

5. There was no particulate emissions data which had been collected from locomotives. A very small amount of particulate data were available on two locomotive type engines which are stationary mounted at Southwest Research Institute. One engine was an EMD product, the other was a GE product. The results of what were largely single tests per engine at each power setting, expressed as grams per brake horsepower hour, (g/BHP-hr) ranged from a low of 0.24 g/BHP-hr to a high of 2.83 g/BHP-hr. It is not known whether these data are representative of locomotive particulate emission rates. Since locomotives use diesel engines, they should possibly be viewed as sources of concern for particulate emissions.*

6. Railroad emissions estimates developed in this study indicate that railroad contributions to the total anthropogenic emissions of hydrocarbons, carbon monoxide and oxides of nitrogen in the five AQCR's studied are in the following ranges: for hydrocarbons the range is from just over one tenth of one percent to one and a third percent; for carbon monoxide the range is from under one tenth of one percent to one-half of one percent and for oxides of nitrogen the range is from two and a third percent to almost fifteen percent. It could not be determined from the data whether areas of concentrated railroad activity constituted a significant source of emissions for adjacent populated areas.

7. Technological approaches for the reduction of NOx emissions from diesel engines generally result in increased particulate emissions (smoke) and increased fuel consumption. Simultaneous reductions in particulate and NOx emissions may be achievable by derating the power of the locomotive. However, if derating were to result in the use of a greater number of locomotives in order to perform the same function (e.g., an additional locomotive on a train), there could be a net increase in total emissions in spite of there being a reduction in emissions from each locomotive.

8. Modification of locomotive duty cycles to reduce the amount of time that locomotive engines are allowed to idle has the potential for reducing railroad emissions as well as being a strategy for fuel conservation. Solutions to several

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* EPA's Office of Research and Development is presently developing a health assessment document for diesel engine emissions. This assessment is being based, in large part, on new epidemiological studies (references 19 and 20) involving exposure of railroad workers with support for diesel particulate exposure by railroad employees derived from data collected from two locomotive type engines by Southwest Research Institute.

technical problems must, however, be developed before this approach to emission control and fuel conservation can be employed under all ambient temperatures.

9. The cost-effectiveness of reducing locomotive emissions appears similar to the cost effectiveness of controls for automobiles, trucks, and motorcycles, but data for making these estimates is very limited.

10. Locomotives remain in service for much longer periods of time than do trucks and passenger cars. If future emissions data warrants the regulation of locomotive emissions, consideration should be given to reducing emissions from in-use locomotives as well as new locomotives.

11. Enforcement of gaseous emissions standards and particulate standards cannot be performed visually as is apparently the present practice for smoke emissions. Development of appropriate test equipment and test cycles would, therefore, be necessary. Information currently available does not indicate what level of difficulty or cost would be associated with the development of test procedures and their implementation.

3.0 RECOMMENDATIONS PERTAINING TO FEDERAL ACTION

This study has shown that there is relatively little data on gaseous emissions and essentially no data on particulate emissions from locomotives and secondary power sources used by the railroad industry. The study has also shown that data pertaining to the application of emission control technology to locomotive engines is lacking. Estimates made in this study of railroad emissions, their control, and their impact on air quality included assumptions in those areas where data were lacking. While the emissions estimates were inconclusive, they suggest that railroads could be viewed with some concern as sources of oxides of nitrogen emissions in some Air Quality Control Regions. To some lesser extent, hydrocarbon emissions from railroads may also be of some concern in some Air Quality Control Regions. Preliminary assessment of technology indicates that control of these emissions may be cost-effective.

It is recommended that sufficient data on locomotive emissions be collected to permit an accurate determination of railroad emissions and their effects. Areas where data collection needs to be emphasized are: 1) particulate emission rates, 2) locomotive duty cycles, 3) the distribution of locomotives throughout the country, and 4) the identification of local concentrations of high emitting locomotives. It is further recommended that techniques for the control of locomotive emissions be evaluated with respect to feasibility of application to both new and in-use locomotives, cost of control and impact on railroad operations. Such studies would reduce the uncertainties contained in present estimates and allow determination of the need for Federal control of railroad emissions.

4.0 BACKGROUND

This section of the report gives a general overview of the study and identifies some characteristics of locomotives and their method of operation which are pertinent to emission patterns of railroad equipment. Modifications of these characteristics with the objective of reducing emissions and fuel consumption constitute part of the section of the report entitled, "Emission Reduction Techniques."

4.1 Selection of Study Areas

Three criteria were used in choosing the Air Quality Control Regions (AQCR) which were analyzed. The first criterion was to meet the Clean Air Act (CAA) requirement that the effects of railroads on air quality be investigated on a nationwide basis. Regions located in several geographic areas of the country were, therefore, chosen. The second criterion was that violations of the National Ambient Air Quality Standards (NAAQS) should either be present in the regions studied or that the regions should have ambient concentrations approaching the standards. The third criteria was that the regions studied should have significant concentrations of railroad traffic. The second and third criteria were used to define areas with pollution problems that may be partially attributable to railroads. It was assumed that if railroads were shown not to be significant contributors to pollution in these regions, then they should not be major contributors in other areas of the country.

Five AQCRs were selected for study on the basis of these criteria. The AQCRs are: Philadelphia, Chicago, St. Louis, Kansas City, and Los Angeles. These AQCRs and the included railroad lines are shown in Figures 1 through 7. These regions are located throughout the nation. The NAAQS for ozone is violated in each of these regions. Kansas City, St. Louis, and Chicago in particular have some of the greatest concentrations of railroad traffic in the nation. The regions selected should, therefore, represent a "worst case" for ozone as related to railroad activity.

4.2 Locomotive Design Characteristics Pertinent to the Study

Diesel locomotives incorporate some design features which are somewhat different to those found in other ground transportation engines. The design features of specific interest in this study are: 1) the design of the engine cooling systems, and 2) the method of controlling engine power.

The first design feature which is of interest in this study is the procedure used in controlling engine coolant

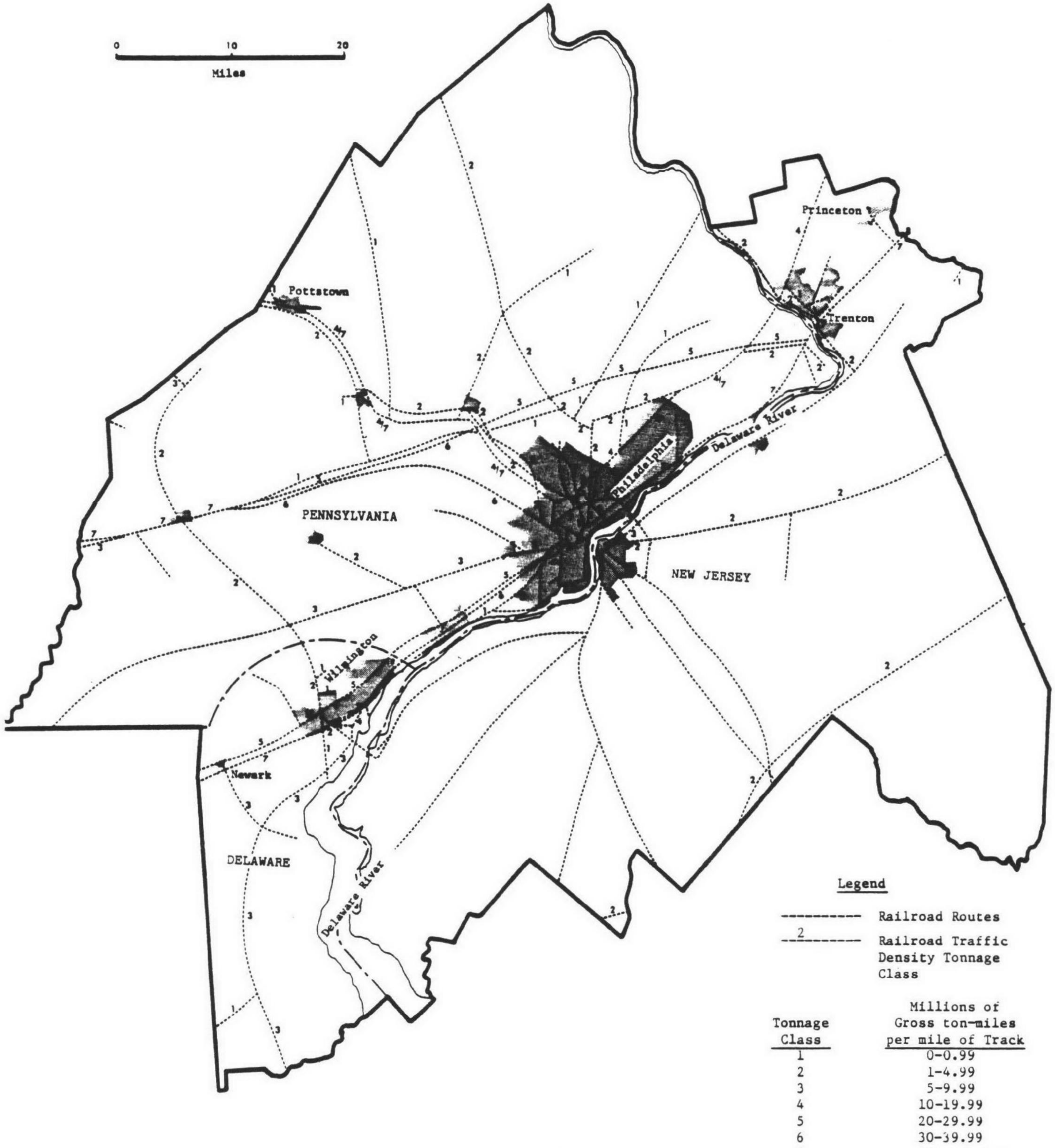


Figure 1

Philadelphia AQCR

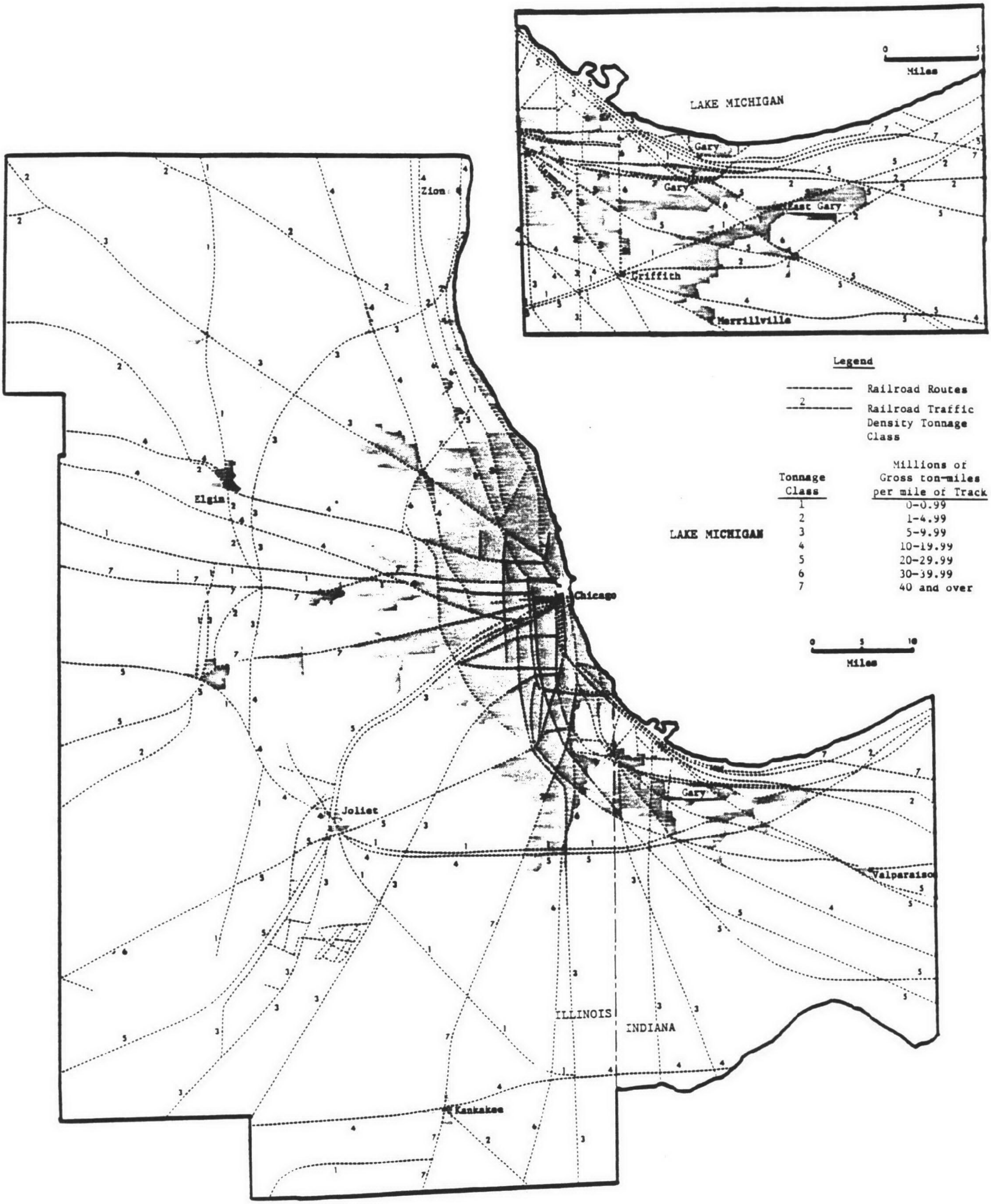


Figure 2

Chicago AQCR

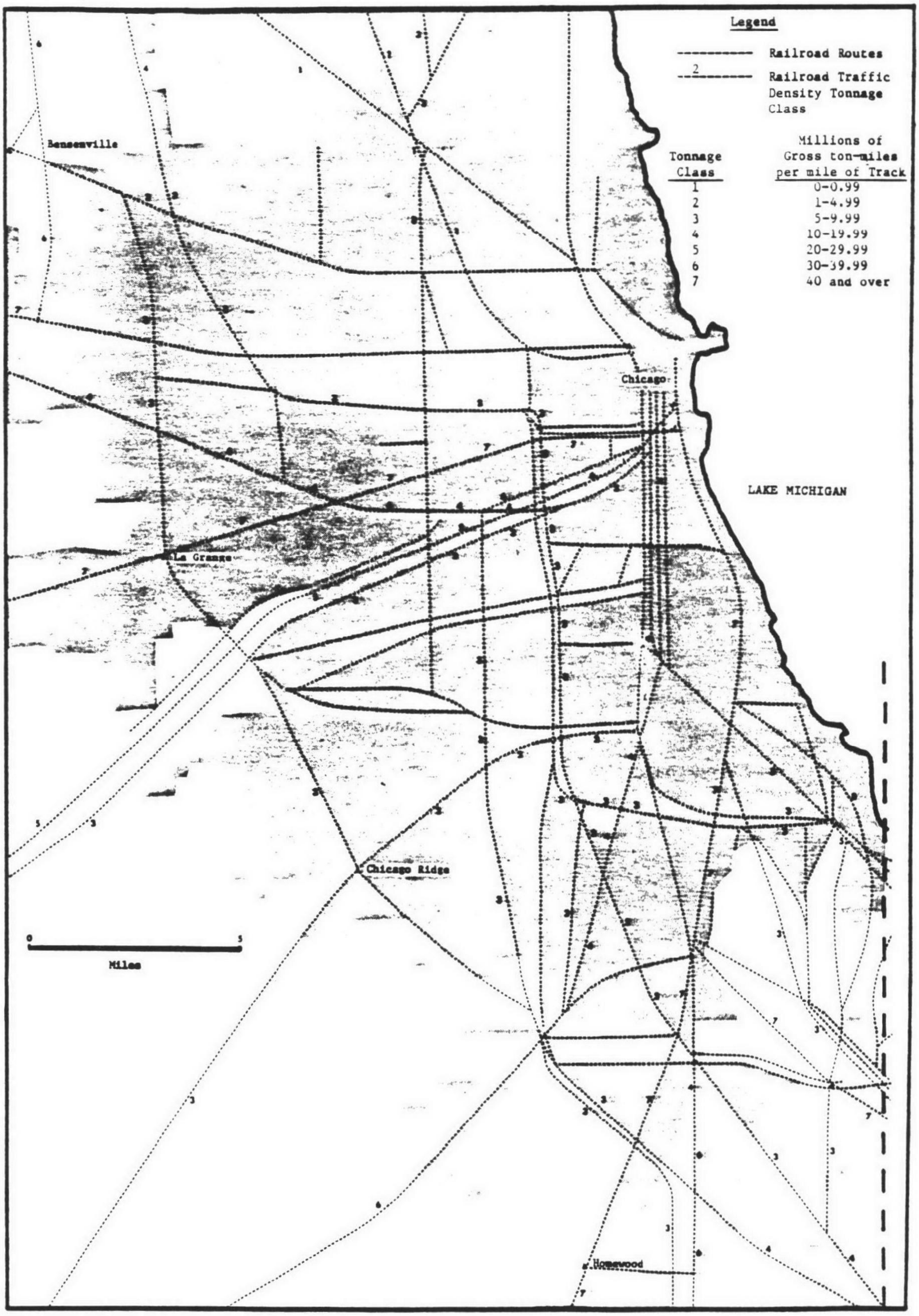
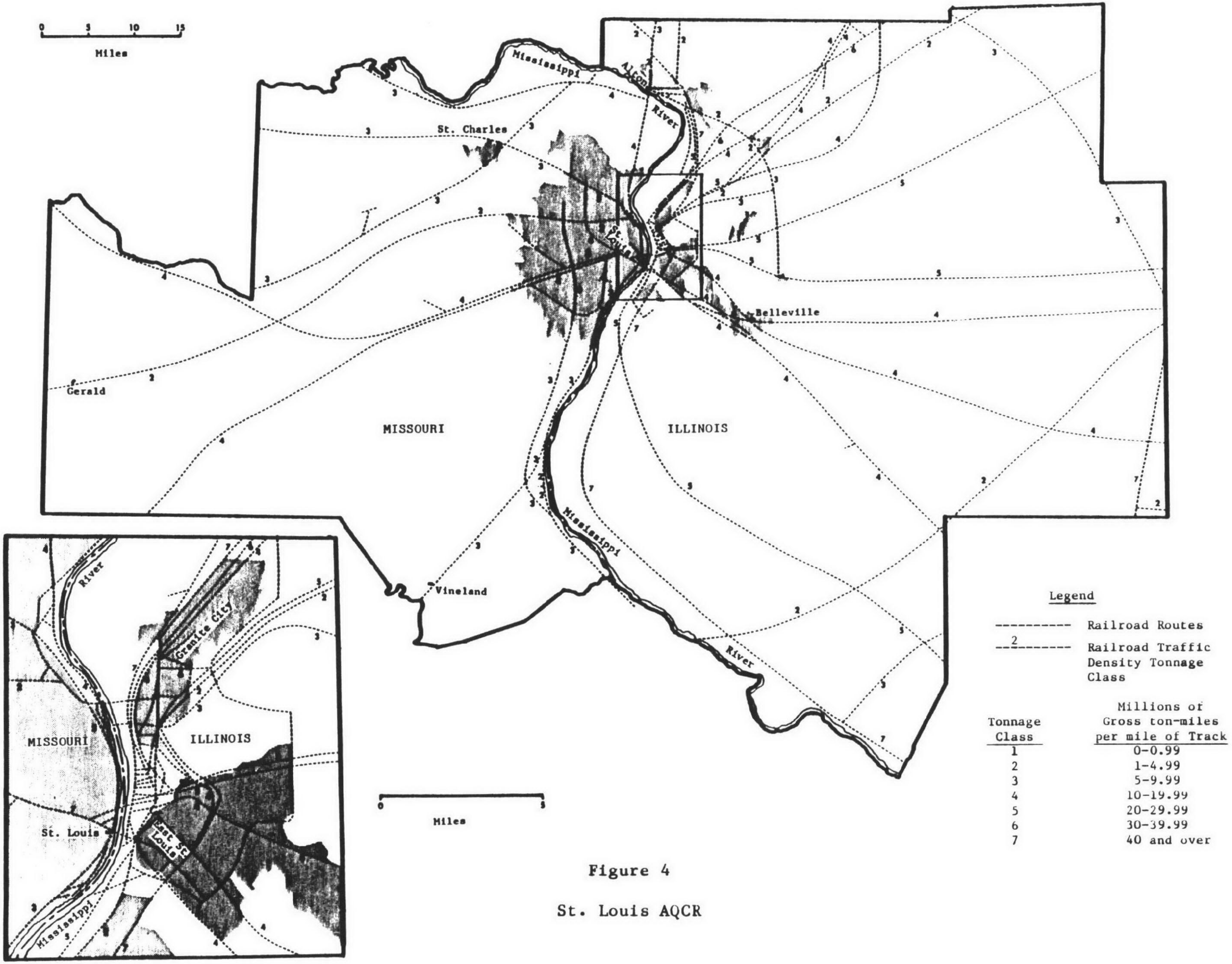


Figure 3

Central Chicago



Tonnage Class	Millions of Gross ton-miles per mile of Track
1	0-0.99
2	1-4.99
3	5-9.99
4	10-19.99
5	20-29.99
6	30-39.99
7	40 and over

Figure 4

St. Louis AQCR

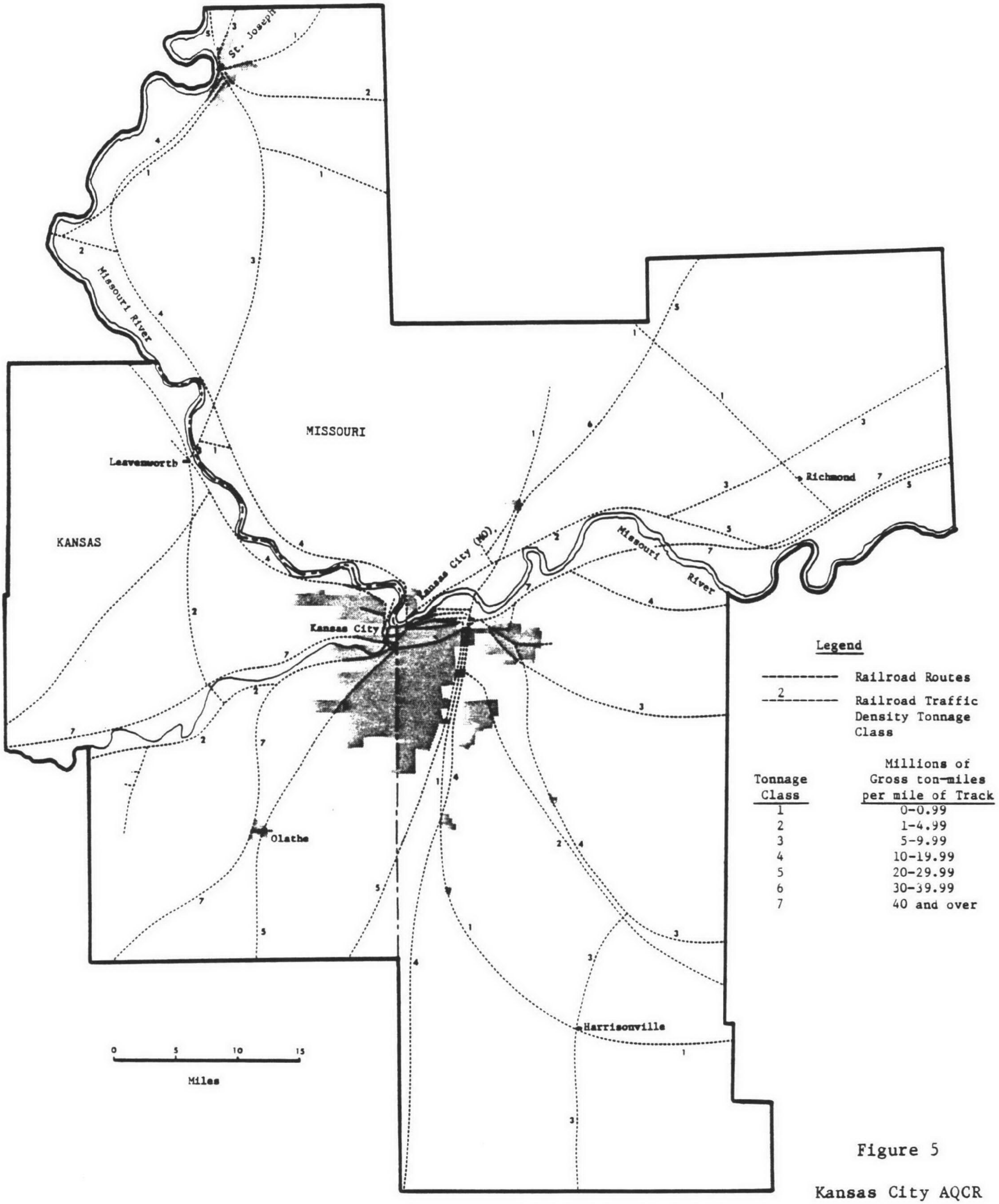


Figure 5

Kansas City AQCR

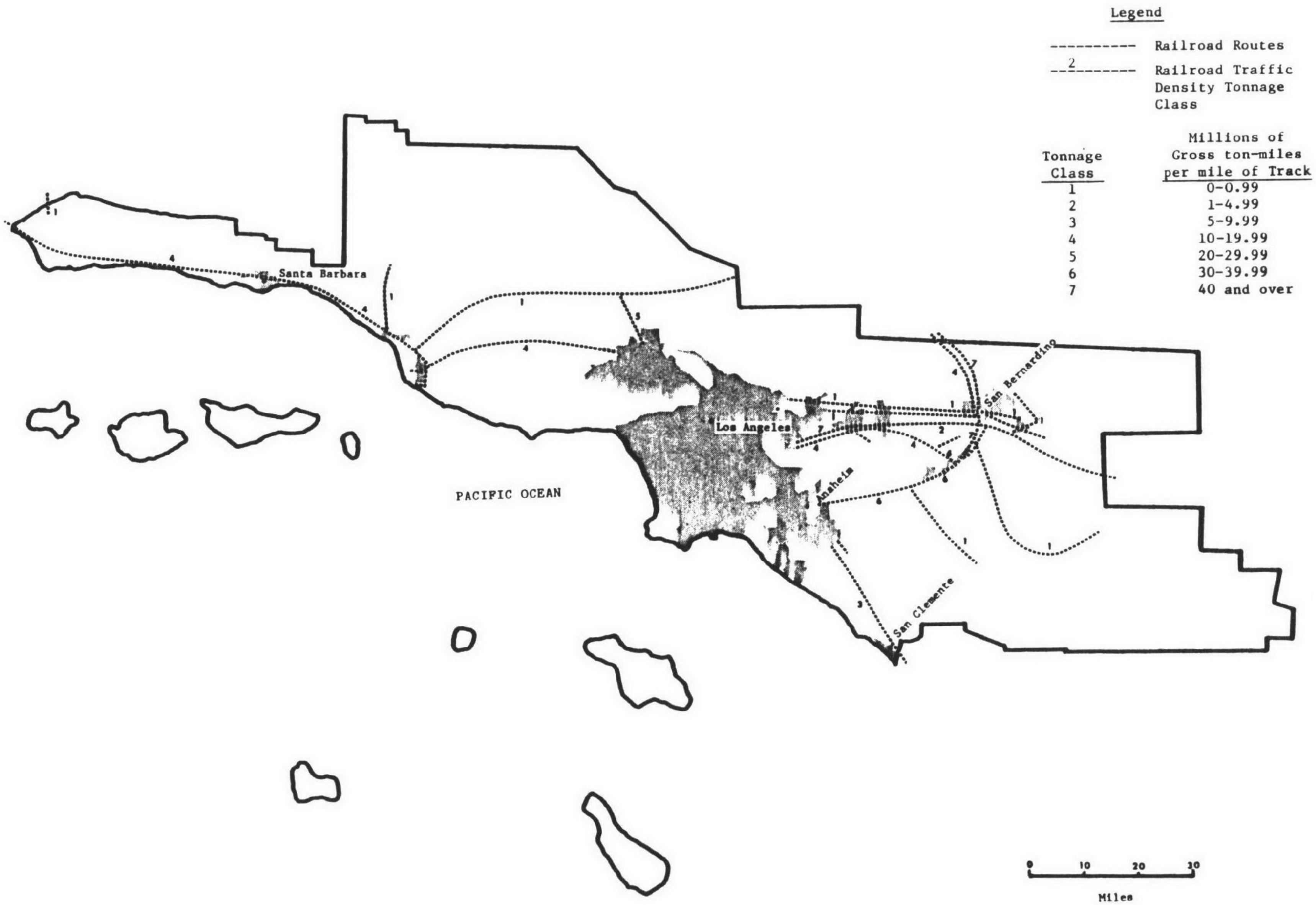


Figure 6

Los Angeles AQCR

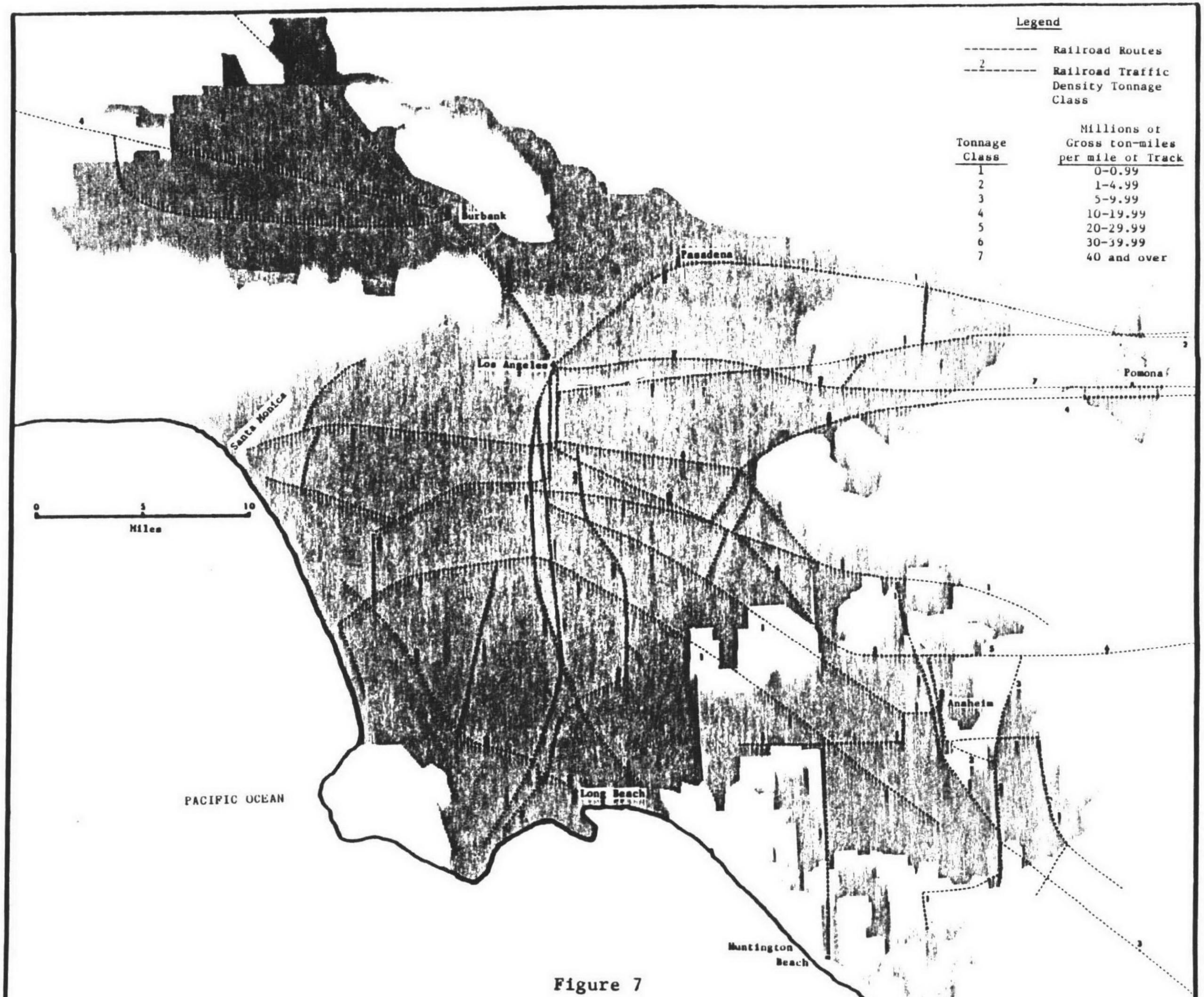


Figure 7

Central Los Angeles

temperature. Normal practice for the control of coolant temperature and, therefore, engine temperature in road vehicles is to thermally separate the coolant into two parts. These two parts or volumes of coolant are located in the engine and in the radiator and are thermally separated by the thermostat. Coolant temperature in the engine and the resulting engine temperature is controlled by the thermostat which regulates the flow of coolant to the radiator. Use of this design approach results in: 1) rapid engine warm-up following a cold start because only a fraction of the coolant in the engine is warmed during engine warm-up, 2) relatively constant coolant temperature and as a result relatively constant engine temperature is maintained as changes in engine load occur, and 3) relatively constant coolant temperature and engine temperature is maintained versus changes in ambient temperature. This approach to the design of engine cooling systems requires the use of an antifreeze to prevent freezing of the coolant in the engine and the radiator during shutdown, and in the radiator when the vehicle is operated in low ambient temperatures.

Normal practice in locomotive design is to treat all of the coolant as a single volume and to control coolant temperature by limiting the capability for heat rejection at the radiator. Two approaches are used on locomotives to limit the ability of the radiator to reject heat. One approach is to control the amount of air flowing across the radiator by use of a variable speed fan drive and shutters while keeping the radiator full of coolant. The other approach is to store that part of the coolant which is not in the engine in a large reservoir and to divert coolant to the radiator as necessary for temperature control, i.e., little or no coolant is normally found in the radiator. This second approach to temperature control of locomotive engines is normally referred to as the dry radiator method. On some newer locomotives where the dry radiator method of control is utilized, air flow across the radiator is also controlled by use of a variable-speed fan. Many older, dry radiator locomotives employ constant-speed fan drives which require a greater amount of power for their operation than that required by the variable-speed fans.

As a result of this cooling system design philosophy, locomotive engines: 1) require an extensive warm-up period following shutdown because not only must the great mass of the engine be warmed but all of the coolant must also be warmed, 2) experience relatively large changes in coolant temperature, and as a result engine temperature, between idle and full power operation, and 3) experience relatively large changes in coolant temperature and engine temperature as a function of ambient temperature. The effects of the cooling system designs on locomotive emissions, within railroad yards, have been that: 1) exhaust emissions (mass basis) from idling locomotives constitute a significant fraction of the total emissions from locomotives, 2) start-up emissions, while the occurrences are infrequent, are higher than would occur if only part of the coolant needed to be warmed up, and 3) emissions levels following a prolonged idle period tend to be high because of the general cooling of the engine.

The second design feature which is peculiar to railroad locomotives and which was of interest in this study 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 the idle and dynamic brake positions. Each notch position is numerically identified, with notch position one being the lowest, off-idle, power setting and position eight being maximum power. In the dynamic brake position, the propulsion system provides a degree of braking. The dynamic brake position is not usually found on switch engines.

The throttle lever in the cab of the locomotive is usually connected to the engine by electrical means as opposed to a mechanical connection. Because of this type of connection, each notch on the throttle corresponds to a discrete setting on the fuel delivery system of the engine and there are no engine power settings which correspond to throttle settings between any two notch positions. The net effect of this method of control is that the engines can operate at only eight distinct power levels, in addition to idle and dynamic brake.

During accelerations, the usual practice for throttle operation is for single notch, stepwise increases in power as opposed to a sweeping change to the highest notch position which will ultimately be employed.

4.3 Locomotive Duty Cycles

The pattern of operation followed by a piece of equipment, expressed in terms such a percent of time at a defined load, speed or other readily identifiable parameter, is usually referred to as the duty cycle for that piece of equipment. The combination of the design of the throttle control and the usual method of operation has permitted locomotive manufacturers and the railroads to establish historical operating patterns or duty cycles for locomotives based upon throttle notch position. This information was of assistance in estimating the emission contributions of railroads within Air Quality Control Regions. Substantial increases in the cost of fuel over the past several years has caused railroads to seek procedures for conserving fuel. One of the procedures which has been introduced is a reduction in the time that locomotives spend at idle. Precise identification of the amount of change which has occurred was not possible, however, because of the lack of recent data on the duty cycle. Historical operating patterns were, therefore, used as the basis in this study.

The locomotive duty cycle describes the amount of time spent in each of the throttle notch positions when a locomotive is available for service. As such, the distribution not only accounts for the time a unit spends engaged in moving freight, but also the time spent at idle, either incurred while the locomotive is awaiting assignment and is not yet an integral part of a train or is part of a train which is stationary. Time during which the locomotive is unavailable for service resulting from factors such as the need for a major overhaul, scheduled maintenance, or inspections would be excluded from the daily duty cycle. Data were not available on the amount of time that locomotives are not available for service. In this analysis it is assumed that on an annual basis, locomotives are unavailable for service for approximately 5 percent of the total time in each year. Expressed as the number of days in which locomotives are not available for service, this 5 percent factor corresponds to 20 days per year. On an annual basis each locomotive is assumed, therefore, to be in service for 345 days.

Within the generic definition of duty cycle, there are two distinct classes of locomotive duty cycle. The classes apply: 1) to line-haul locomotives, and 2) to switch and transfer locomotives. Switch and transfer locomotives generally operate within localized areas and their duty cycles are, therefore, directly applicable within Air Quality Control Regions. Line-haul locomotives cross AQCR boundaries and pose problems, therefore, with respect to the determination of their emissions within an AQCR.*

In an attempt to define the most representative duty cycle for each type of locomotive within each AQCR, historical throttle clock data from the locomotive manufacturers were reviewed. The information available was not adequate to depict

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* The horsepower ratings of locomotives range from a high of about 5,000 hp to under 1,000 hp. The higher power locomotives are usually used for line-haul purposes with the smaller locomotives used in switch and transfer operations. There is no firm rule for distinguishing between the two types of service with respect to the power rating of locomotives. For purposes of this study, all locomotives of 1,500 hp and less were treated as switch and transfer units with the remainder of the locomotives classed as line-haul.

individual regional differences. It is reasonable, however, to expect that the line-haul locomotives of western railroads could spend more time in throttle notch eight (full power) and in dynamic brake (descending long mountain grades) than do their eastern counterparts. This expectation is based on the more mountainous terrain found in the western areas of the country which could entail the extensive use of maximum power when climbing grades and dynamic brake when descending grades. Since duty cycles for each region could not be formulated, it was decided to use the existing industry duty cycles with some modifications where appropriate.

4.3.1 Switch and Transfer Locomotive Duty Cycle

Generally, switch locomotives operate within a switchyard or terminal area, while transfer locomotives move rail cars between switchyards and are involved in branchline service where rail cars are delivered to or received from customers. Switch and transfer locomotives are typically smaller, lower power units.

The literature contains two duty cycles for switch locomotives (Table 1). The literature does not contain any duty cycles for transfer locomotives. It was not possible, therefore, to distinguish between duty cycles for switch and transfer locomotives. It was assumed that locomotives employed in transfer service experience the same duty cycle as those employed in switch service and a single duty cycle was used for these two types of service. As shown in Table 1, the two switch locomotive duty cycles are nearly identical. Dynamic brake is not included in these cycles because switch locomotives are not usually equipped with this feature.* The Atchinson, Topeka, and Santa Fe Railroad cycle (ATSF) was apparently based on only that railroad's operating experience. The Electromotive Division of General Motors (EMD) cycle was chosen to be more representative of national operations since it seems likely that it was generated from throttle clock data recorded from several railroads. The duty cycle for switch and transfer locomotives represents operation on a 24 hour per day basis for each day of the year that the locomotive is in service.

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* During dynamic brake operation, the function of the locomotive powerplant (engine, generator and traction motors) is reversed and the powerplant serves as a brake.

Table 1

Switch Locomotive Duty Cycles

Throttle Notch Position	Percent of Time in Each Notch, Per 24-Hour Day	
	ATSF[1]	EMD[1]
Engine Off	0	0
Idle	77	77
Notch 1	10	7
Notch 2	5	7
Notch 3	4	4
Notch 4	2	2
Notch 5	1	1
Notch 6	1	0.5
Notch 7	0	0.5
Notch 8	0	1

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[1] ATSF - Atchinson, Topeka and Santa Fe.
EMD - Electromotive Division, General Motors.

4.3.2 Line-Haul Locomotive Duty Cycle

Duty cycles which have been developed by the railroad industry and by locomotive manufactures for line-haul locomotives are shown in Table 2. The EMD heavy-duty cycle, the General Electric (GE) maximum cycle and the Association of American Railroads (AAR) duty cycles may be most representative of locomotive operation between cities or western railroad service in general. The EMD medium-duty cycle and the GE average duty cycles are probably most typical of overall line-haul freight operations on a national basis.

Since the throttle notch data upon which these cycles are based were derived from a combination of intercity and intracity operations, the data would not be expected to precisely define operations within the metropolitan/suburban AQCRs under study. It was concluded, therefore, that the industry duty cycles having high percentages of throttle notch eight operation were inappropriate for use within AQCRs. Two reasons predominate in arriving at this conclusion. The first reason is the lower average speed of trains when operating in the metropolitan regions as compared to the long intercity distances where higher speeds are maintained. Operation of the locomotive in the highest power settings (notches seven and eight) would, therefore, tend to be emphasized during intercity operation. Second, although trains are accelerating as they leave the switchyards or other congested areas, and as a result require the use of relatively high power settings, it is not normal operating practice to "sweep" the throttle from a low notch position to notch seven or eight. Each higher notch position of the throttle is not normally selected until a significant portion of the ultimate power in the preceding notch has been achieved. Because accelerations are accomplished with an orderly and gradual progression to higher notch positions, a relatively small amount of time is accumulated in the highest notches. At reduced speeds, dynamic brake becomes inefficient and its excessive use could damage the traction motor of the locomotive because of poor heat transfer characteristics. The percentage of time spent in dynamic braking within an AQCR is, therefore, expected to be less than that which exists for the overall operation of line-haul locomotives.

On this basis, EPA selected the General Electric minimum-duty cycle for line-haul locomotives as the basis for representative operation within an AQCR (Table 3). The values selected for the percentage of time spent in each notch were rounded to whole numbers so as to avoid the appearance of great accuracy. In applying the duty cycle selected for line-haul locomotive operation in an AQCR, it was assumed that 50 percent of the total line-haul locomotive operational time was spent within AQCRs and the other 50 percent was spent in rural

Table 2

Line-Haul Locomotive Duty Cycles

Throttle Notch Position	Percent of Time in Each Notch Per 24-Hour Day						
	GE1/ Min.	GE Max.	GE Avg.1	GE Avg.2	EMD Heavy1/	EMD Med.	AAR1/
Engine Off	0	0	0	0	0	0	0
Idle	59.0	40.0	54.0	53.0	41.0	46	43.0
Notch 1	6.5	2.5	5.0	5.1	3.0	4	3.0
Notch 2	6.5	2.5	2.5	3.9	3.0	4	3.0
Notch 3	6.5	2.5	2.0	3.4	3.0	4	3.0
Notch 4	6.5	2.1	5.0	3.3	3.0	4	3.0
Notch 5	2.9	1.7	2.0	2.8	3.0	4	3.0
Notch 6	2.9	1.7	2.0	3.4	3.0	4	3.0
Notch 7	2.5	1.8	2.5	2.6	3.0	4	3.0
Notch 8	5.2	38.0	21.0	17.0	30.0	17	28.0
Dyn. Brake	1.5	7.0	4.0	5.5	8.0	9	8.0

1/ AAR - Association of American Railroads.
GE - General Electric.
EMD - Electromotive Division, General Motors.

Table 3

Line-Haul Locomotive Duty Cycle Applicable to Operation Within Air Quality Control Regions

Throttle Notch Position	Percent of Time in Each Notch, Per 12-Hour Day
Engine Off	0
Idle	59
Notch 1	7
Notch 2	6
Notch 3	6
Notch 4	6
Notch 5	3
Notch 6	3
Notch 7	3
Notch 8	5
Dyn. Brake	2

areas. The duty cycle for rural line-haul locomotive operation was calculated* (Table 4) and compared to the maximum-duty cycles as a check of the assumptions which had been made. Because of the similarity between the calculated rural-duty cycle and the AAR, EMD heavy-duty and GE maximum-duty cycles, it was concluded that the assumptions were reasonable.

4.3.3 Secondary Power Source Duty Cycle

The third duty cycle used in this study was that of the relatively small diesel engines used to operate the refrigeration systems of refrigerated rail cars. This group of engines constitute the secondary power sources which are found on trains.

The duty cycle for these engines was obtained from Pacific Fruit Express (PFE 1978). This cycle (Table 5) is based on transcontinental shipments lasting approximately ten days. The cargo in this instance is not pre-cooled; hence, the cycle is more rigorous than if pre-cooled or pre-frozen food was to be transported. For the purposes of this analysis, the duty cycle is assumed to occur over a 24 hour period for each refrigerated rail car that is in service in an AQCR.

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* Difference between time spent in a throttle notch position in medium duty cycle on a 24 hour basis and time spent in the same throttle notch position in minimum duty cycle on a 12 hour basis gives the time spent in the same throttle notch position in the calculated rural duty cycle on a 12 hour basis.

Table 4

Line-Haul Locomotive Duty Cycles Overall Average, Within AQCRs and In Rural Areas

Throttle Position	Overall Average[1]	Within AQCR[2]	In Rural Areas[3]
Engine Off	0	0	0
Idle	51	59	43
Notch 1	5	7	3
Notch 2	4	6	2
Notch 3	3	6	0
Notch 4	4	6	2
Notch 5	3	3	3
Notch 6	3	3	3
Notch 7	3	3	3
Notch 8	18	5	31
Dynamic Brake	6	2	10

1/ Average of two G.E. average cycles and EMD medium cycle and applicable to total time; i.e., 24 hours per day.

2/ Based on G.E. minimum cycles and applicable to one-half of total time, i.e.,12 hours per day.

3/ Based on difference between hours spent in each notch of the overall average and within AQCRs cycles.

Table 5

Refrigerated Rail Car
Duty Cycle and Engine Loading

Mode	Percentage of Time in Mode	Engine Speed (rpm)	Rated Power @ Speed	Percent of Rated Power @ Speed
Maximum Cool	10	1,200	33 @ 1,200	95% @ 1,200
High Speed Cool	10	1,200	33 @ 1,200	72% @ 1,200
Low Speed Cool	50	800	20 @ 800	67% @ 800
Low Speed - No Cooling	30	800	20 @ 800	20% @ 800

5.0 RAILROAD EMISSION ESTIMATES

Three parameters were used in the development of the estimates of railroad exhaust emissions within the five Air Quality Control Regions which were studied. The parameters used were: 1) the locomotive and refrigerated rail car duty cycles previously developed, 2) exhaust emissions from locomotives and refrigerated rail car engines, and 3) the number of locomotives and refrigerated rail cars in use in each Air Quality Control Region.

5.1 Locomotive Exhaust Emissions

Three sets of data on locomotive emissions were utilized in developing estimates of individual source exhaust emissions. Southwest Research Institute (SwRI) tested three locomotives as part of Contract Number EHS 70-108 for the Environmental Protection Agency.[1] This work was performed in 1971-72. The locomotives tested were in-use units obtained from Southern Pacific and included a 1200 hp EMD switch engine, a 3000 hp EMD line-haul engine and 3600 hp GE line-haul engine.

The second set of data on locomotive emissions was furnished by EMD. This data set consisted of data taken from new locomotives in 1978. The data were presented as mean results from nine 1500 hp engines, eighteen 2000 hp engines and twenty-two 3000 hp engines. The standard deviations of the data were also presented. The third and largest set of data was provided by the Association of American Railroads (AAR). This data set was collected by AAR between 1981 and 1983. The data were presented as the means and standard deviations for each of the groups of engines tested. In total, fifty seven in-use locomotives were tested. On a manufacturer basis, the locomotives tested were as follows: EMD; sixteen 2000 hp engines, two 2250 hp engines, four 2500 hp engines, fifteen 3000 hp engines and eight 3600 hp engines; G.E; five 3000 hp engines and seven 3600 hp engines. Within this data set the engines tested were divided into two groups. One group consisted of engines which were tested immediately after a major overhaul. The other group consisted of engines which were tested just prior to the performance of a major overhaul. In utilizing this data (AAR data) EPA treated the data collected from engines immediately after a major overhaul as being equivalent to new locomotive data.

The estimates of in-use locomotive emissions were developed from the three data sets as follows. In the first step, the emission data on each engine type (e.g., the 3000 hp EMD locomotive) from each source were inspected to determine whether the data were similar or dissimilar. Since the test data on each engine tested in each data set were not provided, an approximate rather than a statistically precise determination of similarity or dissimilarity was made. Test results from the three data sources on locomotives of the same specification were treated as being similar when the difference between the mean results was less than the sum of the standard deviations for the majority of the data on that locomotive type. Application of this test for similarity or dissimilarity between data sets resulted in the removal from the data base of one set of test results on a single locomotive (the 3000 hp EMD locomotive tested by SwRI in 1971-1972).

The second step in the development of the estimates of emissions from in-use locomotives was the calculation of "new" locomotive and "used" locomotive (i.e., locomotives approaching a major overhaul) emission rates. "New" locomotive emissions were derived from the data supplied by EMD and from the AAR data on locomotives immediately following a major overhaul. "Used" locomotive emissions were derived from the AAR data on locomotives approaching a major overhaul and from SwRI data. Since the means of the emission results contained in each data set were obtained from differing sample sizes, the average "new" and average "used" emission rates were calculated as sampling size weighted means; i.e., the sum of the products of mean sample emissions and sample size was divided by the sum of the sample sizes to develop the average "new" and average "used" locomotive emissions. Implicit within this calculational methodology is the assumption that changes in locomotive emissions occur linearly with time.

The third step in the development of in-use locomotive emissions estimates was the calculation of the emissions rates, for "average" in-use locomotives of the types tested. This calculation utilized the assumption that there is a linear change in emission rates as locomotives age from the "new" to the "used" condition. With this assumption, emissions from an average locomotive are calculated as the mathematical average of the new and used values. The emissions rates for average locomotives of the eight specifications tested are shown in Tables 6 through 8. Hydrocarbon emissions are shown in Table 6, carbon monoxide emission in Table 7 and oxides of nitrogen emission are shown in Table 8. The units employed are grams of pollutant per hour of operation in each throttle notch position.

The fourth step in the procedure was the calculation of the in-use weighted average emissions for line-haul and for switch and transfer locomotives. Since there are a greater number of horsepower ratings for in-use locomotives than there are power ratings in the data base, a degree of grouping of the in-use locomotives was necessary. The in-use locomotives were grouped so that the ratings of the test locomotives were equal to the power ratings of the greater number of in-use

Table 6

Average Locomotive Hydrocarbon Emissions by Throttle Setting

Locomotive Emissions (g/hr)

Throttle Notch	EMD[1] 3600 hp	GE[2] 3600 hp	EMD[3] 3000 hp	GE[4] 3000 hp	EMD[5] 2250/2500 hp	EMD[6] 2000 hp	EMD[7] 1500 hp	EMD[8] 1000 hp
Idle	251	835	228	532	231	152	97	387
1	193	822	201	608	170	146	93	452
2	200	4,511	236	1,177	180	169	116	638
3	259	9,728	316	2,220	219	224	145	984
4	306	7,922	382	3,359	256	304	193	1,482
5	422	8,781	544	3,850	339	428	271	1,830
6	529	8,786	728	4,029	425	571	367	2,387
7	767	8,840	1,002	5,330	565	789	517	2,960
8	971	10,044	1,276	6,234	806	1,005	660	3,976
Dyn Brake	363	1,941	366	2,271	316	252	-	-

Data Source, time frame of testing, number of engines tested
1/ AAR, 1981-1983, 9 engines.
2/ AAR, 1981-1983, 3 engines; SwRI, 1971-1972, 1 engine.
3/ AAR, 1981-1983, 12 engines; EMD, 1978, 22 engines.
4/ AAR, 1981-1983, 7 engines.
5/ AAR, 1981-1983, 6 engines.
6/ AAR, 1981-1983, 16 engines; EMD, 1978, 18 engines.
7/ EMD, 1978, 9 engines.
8/ SwRI, 1971-1972, 1 engine.

Table 7

Average Locomotive Carbon Monoxide Emissions by Throttle Setting

	Locomotive Emissions (g/hr)							
Throttle Notch	EMD1/ 3600 hp	GE2/ 3600 hp	EMD3/ 3000 hp	GE4/ 3000 hp	EMD5/ 2250/2500 hp	EMD6/ 2000 hp	EMD7/ 1500 hp	EMD8/ 1000 hp
Idle	588	481	566	1,048	599	291	174	160
1	432	658	392	962	316	208	184	273
2	484	1,588	362	2,236	304	350	295	341
3	610	2,325	466	3,858	378	441	337	481
4	720	3,036	570	7,964	448	458	351	560
5	1,033	3,721	1,160	8,504	832	616	416	702
6	2,480	4,466	2,591	12,038	2,122	1,120	659	768
7	3,849	4,454	5,036	8,339	5,060	2,686	1,959	1,052
8	4,472	5,099	6,092	7,892	9,868	5,704	5,305	1,844
Dyn Brake	818	2,352	840	2,780	635	702	-	-

Data Source, time frame of testing, number of engines tested

1/ AAR, 1981-1983, 9 engines.
2/ AAR, 1981-1983, 3 engines; SwRI, 1971-1972, 1 engine.
3/ AAR, 1981-1983, 12 engines; EMD, 1978, 22 engines.
4/ AAR, 1981-1983, 7 engines.
5/ AAR, 1981-1983, 6 engines.
6/ AAR, 1981-1983, 16 engines, EMD, 1978, 18 engines.
7/ EMD, 1978, 9 engines.
8/ SwRI, 1971-1972, 1 engine.

Table 8

Average Locomotive Oxide of Nitrogen Emissions by Throttle Setting

Throttle Notch	EMD[1/] 3600 hp	GE[2/] 3600 hp	EMD[3/] 3000 hp	GE[4/] 3000 hp	EMD[5/] 2250/2500 hp	EMD[6/] 2000 hp	EMD[7/] 1500 hp	EMD[8/] 1000 hp
	Locomotive Emissions (g/hr)							
Idle	1,561	978	1,448	977	1,434	1,059	957	335
1	2,331	4,083	3,105	2,009	1,765	1,506	1,248	626
2	3,534	11,880	5,367	5,023	3,163	3,461	2,763	920
3	5,852	14,944	9,091	13,120	4,794	6,497	5,605	2,003
4	8,685	19,343	13,282	17,871	6,773	10,648	9,598	3,218
5	11,808	23,427	18,626	25,023	9,306	15,617	13,932	4,946
6	15,436	28,061	23,337	29,354	11,879	21,054	17,743	6,718
7	24,774	28,666	30,344	34,262	15,287	27,112	21,623	8,367
8	29,809	33,050	36,409	42,750	23,859	31,388	23,864	10,220
Dyn Brake	3,540	5,043	1,771	5,798	2,486	3,255	-	-

Data Source; time frame of testing, number of engines tested

1/ AAR, 1981-1983, 9 engines.

2/ AAR, 1981-1983, 3 engines; SwRI, 1971-1972, 1 engine.

3/ AAR, 1981-1983, 12 engines; EMD, 1978, 22 engines.

4/ AAR, 1981-1983, 7 engines.

5/ AAR, 1981-1983, 6 engines.

6/ AAR, 1981-1983, 16 engines, EMD, 1978, 18 engines.

7/ EMD, 1978, 9 engines.

8/ SwRI, 1971-1972, 1 engine.

locomotives in each in-use group. The horsepower groupings of in-use locomotives, the number of in-use locomotives in each group and the horsepower ratings of the test-engines used to represent the in-use groups are shown in Table 9.

The calculation of the in-use weighted emissions averages was performed by summing the products of the emission rates for the test engines and the number of in-use engines in the group so represented and dividing by the total number of in-use locomotives in the group. The results of these calculations are shown in Table 10 for line-haul locomotives and in Table 11 for switch and transfer locomotives.

The fifth and final step in the procedure was the calculation of locomotive emissions in each AQCR under study. This step was performed by determining the daily emissions of "average" line-haul and switch and transfer locomotives when in an AQCR and multiplying by the number of locomotives of each type in the AQCR and the number of days per year that each locomotive is in service (i.e., 345 days).

The procedures used for developing the duty cycles were described in the Background section of this report. These duty cycles were employed in this calculation.

The daily (i.e., duty cycle weighted) locomotive emissions were calculated by determining the product of the emissions in each throttle notch and the number of hours spent in each throttle notch position and summing the values so calculated. The results of these calculations are shown in Tables 12 and 13. As can be seen from these tables, an average line-haul locomotive emits on a daily average basis 14.43 lb. of HC, 31.03 lb. of CO and 160.49 lb. of NOx, while an average switch and transfer locomotive emits 15.28 lb., 13.58 lb. and 77.66 lb. of HC, CO, and NOx respectively.

Estimation of the number of locomotives in each AQCR was performed by extrapolating from information supplied by the Federal Railroad Administration (FRA). For the 1978-1979 timeframe, FRA safety inspectors provided EPA with data on the number of switch and transfer locomotives in the AQCRs being studied. This information was used to extrapolate to the total number of locomotives in an AQCR by assuming that there is a direct relationship between the number of switch and transfer locomotives in a region and the number of line-haul locomotives serving that region. The assumption is that the fraction of the total number of line-haul locomotives serving any region is the same as the fraction of the total number of switch and transfer locomotives operating in that region. The rationale leading to this assumption is that there should be a relatively fixed relationship between the number of line-haul locomotives

Table 9

In-Use Locomotive Power Rating Groups, Number of Locomotives by Groups, and Test Engines Representing In-Use Groups

	Locomotive groupings by power level							
	Line-Haul						Switch and Transfer	
In-Use Horsepower Group	EMD 3300 hp & Over	GE 3200 hp & Over	EMD 3200 thru 2800 hp	GE 3000 thru 1800 hp	EMD 2700 thru 2250 hp	EMD 2000 thru 1600 hp	EMD 1500 thru 1300 hp	EMD 1200 hp & under GE 1000 hp & under
Number of Locomotives in group	1,753	655	5,818	2,386	2,402	6,192	2,807	2,003 EMD 72 GE
Test Engine Power Rating	EMD 3,600 hp	GE 3,600 hp	EMD 3,000 hp	GE 3,000 hp	EMD 2,500 and 2,250 hp	EMD 2,000 hp	EMD 1,500 hp	EMD 1,200 hp

Table 10

In-Use Weighted Average Line-Haul Locomotive Emissions By Throttle Position

Throttle Position	Emissions (gm/hr per locomotive)		
	HC	CO	NOx
Idle	264	540	1,257
1	250	407	2,248
2	467	637	4,489
3	827	945	8,121
4	961	1,535	11,976
5	1,161	1,932	16,826
6	1,306	3,286	21,355
7	1,662	4,564	27,340
8	2,017	6,481	33,291
Dynamic Brake	613	1,060	3,112

Table 11

In-Use Weighted Average Switch and Transfer Locomotive Emissions By Throttle Position

Throttle Position	Emissions (gm/hr per locomotive)		
	HC	CO	NOx
Idle	220	168	692
1	246	222	983
2	338	315	1,979
3	502	398	4,073
4	741	440	6,884
5	934	538	10,110
6	1,226	705	13,053
7	1,556	1,573	15,984
8	2,071	3,833	18,060

Table 12

Line-Haul Locomotive Emissions Per Locomotive, Per 12-Hour Day in an AQCR

Throttle Position	Duty Cycle	Operating Hours	Emissions (pounds/day)		
			HC	CO	NOx
Idle	59	7.08	4.12	8.44	19.61
1	7	0.84	0.46	0.75	4.16
2	6	0.72	0.74	1.01	7.13
3	6	0.72	1.31	1.50	12.89
4	6	0.72	1.53	2.44	19.01
5	3	0.36	0.92	1.53	13.35
6	3	0.36	1.04	2.61	16.95
7	3	0.36	1.32	3.62	21.70
8	5	0.60	2.67	8.57	44.04
Dynamic Brake	2	0.24	0.32	0.56	1.65
Total	100	12.00	14.43	31.03	160.49

Table 13

Switch and Transfer Locomotive Emissions Per Locomotive, 24-Hours Per Day

Throttle Position	Duty Cycle	Operating Hours	Emissions (pounds/day)		
			HC	CO	NOx
Idle	77	18.48	8.96	6.85	28.19
1	7	1.68	0.91	0.82	3.64
2	7	1.68	1.25	1.67	7.33
3	4	0.96	1.06	0.84	8.62
4	2	0.48	0.78	0.47	7.29
5	1	0.24	0.49	0.29	5.35
6	0.5	0.12	0.32	0.19	3.45
7	0.5	0.12	0.41	0.42	4.23
8	1	0.24	1.10	2.03	9.56
Total	100	24.00	15.28	13.58	77.66

which service an area and the number of switch and transfer locomotives which service the line-haul locomotives, because switch and transfer locomotives are used to process the freight cars which enter and leave a region (freightyard, for example). The numerical values for these distributions, adjusted to the number of locomotives in service in 1984,[2] are given in Table 14.

Line-haul and switch and transfer locomotive emissions for each AQCR, expressed as tons per year, are shown in Table 15.

5.2 Secondary Power Sources Exhaust Emissions

Emissions from refrigerated rail cars (secondary power sources) were calculated as described below and the resulting contributions in each AQCR are shown in the railroad emissions summary table.

Two basic types of refrigerated rail car are currently in service throughout the nation. These types are nonmechanical and mechanical refrigerated rail cars. Nonmechanical units utilize either block ice, a mixture of crushed ice and salt, or solid carbon dioxide (dry ice) as the cooling medium. Mechanical units are powered by an internal combustion engine. In this analysis, only mechanical refrigerated units were considered since only these units have exhaust emissions while in the railroad system.

Mechanical refrigeration units use a relatively small diesel engine to generate electric power which operates the refrigeration system. In addition, most cars are equipped with an electrical heating system. This system is used to defrost the car's interior or, in winter, to protect perishables from freezing temperatures. Consequently, most refrigerated cars are capable of maintaining internal temperatures of from -20°F to +70°F and may be operated throughout the year. These cars are also used without their mechanical refrigeration devices in operation when nonperishable commodities do not require protection from temperature extremes.

A review of alternative methods for quantifying the number of refrigerated cars in each AQCR concluded that the most accurate assessment could be made by basing refrigerated car population estimates on actual in-use data obtained from the analysis of rail operations being conducted by the Chicago Terminal Project. This project was jointly funded by the Federal Railroad Administration and the Association of American Railroads. EPA was not, however, able to secure the desired data from this source and had to adopt an alternative method.

Table 14

Number of Locomotives in Each AQCR

AQCR	Switch and Transfer Locomotives		Line-Haul Locomotives	
	Percentage of Total[1]	Number of Units[2]	Percentage of Total	Number of Units[3]
Philadelphia	1.62	79	1.62	311
Chicago	13.13	641	13.13	2,522
St. Louis	2.06	101	2.06	396
Kansas City	2.25	110	2.25	432
Los Angeles	1.99	97	1.99	382

1/ Percentage of total switch and transfer locomotives derived from count of switch and transfer locomotives in service in each city as furnished by Federal Railroad Administration in 1979, divided by total number of switch and transfer locomotives in service in 1979.

2/ Number of switch and transfer locomotives in each AQCR derived from the percentage of the total number of switch and transfer locomotives and the total number in service in 1984.

3/ Number of line-haul locomotives in each AQCR derived from the percentage of the total number of switch and transfer locomotives and the total number of line-haul locomotives in service in 1984.

Table 15

Line-Haul and Switch and Transfer Locomotive Emissions in Five AQCRs

AQCR	Emissions (tons/year) HC	CO	NOx
Philadelphia:			
Line Haul	774	1,665	8,610
Switch	208	185	1,058
Chicago:			
Line Haul	6,278	13,499	69,820
Switch	1,690	1,502	8,587
St. Louis:			
Line Haul	986	2,120	10,963
Switch	266	237	1,354
Kansas City:			
Line Haul	1,075	2,312	11,960
Switch	290	258	1,473
Los Angeles:			
Line Haul	951	2,045	10,575
Switch	256	227	1,300

Refrigerated car activity was approximated by weighting the national population of these units by the amount of traffic in each region (Table 16). This method assumes that refrigerated units are equally distributed throughout the nation based on the amount of freight moved in each area. This may underestimate refrigerated car operations in large market areas and rail terminals which, because of high demand and longer car residence times, would tend to agglomerate larger concentrations of these units, e.g., Philadelphia, Chicago, St. Louis, and Kansas City. The possibility of overestimation exists in smaller markets and producing areas, e.g., the Los Angeles region. However, the existence of a major port facility in Los Angeles may moderate this effect.

The literature contains inconsistent population estimates of the nation's mechanical refrigerator cars. A statistical summary for the years 1966-76 published by the AAR (1977), reported 9,259 mechanical and 3,613 nonmechanical units in 1976. This compares favorably with rail statistics published by the Interstate Commerce Commission (ICC 1976). Both sources are based on ICC annual reports, which are submitted by each Class I railroad (railroads are grouped into classes, with Class I railroads being the largest). In the Yearbook of Railroad Facts (AAR 1977), the total for all refrigerated cars owned by Class I railroads is given as 74,936. The difference between the two AAR documents for refrigerated cars is approximately 62,000 units. Moreover, the figures from AAR's statistical summary (AAR 1977) are internally inconsistent. In 1967, the total refrigerated car population was reported to be 49,399, but one year later in 1968 the total population was reported as 15,638.

To determine the exact number of refrigerated cars in the nation, the AAR Car Service Division was contacted (AAR 1978). According to the CS-8A report from the Train II system, 30,106 diesel-electric refrigerator cars were in service as of January 1, 1977. This information is reported directly from the car owners to the AAR. Therefore, this figure represents the 1976 national fleet of these cars owned by Class I and II railroads (large railroads) as well as other companies and shippers and was used by the EPA in the estimation of emissions from secondary power sources.

Table 16 shows the average number of refrigeration units which reside in each region at any one time. As a worst case condition, it is assumed that each of the diesel-electric units is in operation 24 hours a day. The same number of days per year wherein the units are actually in service was assumed for refrigerated cars as had been used for locomotives.

Table 16

Refrigerated Rail Cars in Each AQCR

AQCR	Percent Traffic (AQCR to Total)	Total Diesel-Electric Units[1]	Regional Diesel-Electric Units
Philadelphia	0.57	30,106	172
Chicago	2.26	30,106	680
St. Louis	1.11	30,106	334
Kansas City	0.68	30,106	205
Los Angeles	0.84	30,106	253

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[1] AAR (1978).

Mechanical refrigeration units typically use the Detroit Diesel-Allison 2-71 engine. This 2-stroke, 2-cylinder diesel engine is nominally rated for 68 horsepower at 2,000 rpm. The EPA has no exhaust emission data on the Detroit Diesel-Allison 2-71 engine. Emission tests on a similarly configured engine from the same manufacturer have, however, been made. Emission rates for this engine, the Detroit Diesel-Allison 6V-71, were determined by the Southwest Research Institute (Hare and Springer 1973). Because this engine, the 6V-71, is essentially three 2-71 engines mounted on a common crankshaft, the mechanical refrigerated car emission rates (Table 17) for each of the modes of operation in the duty cycles were developed by dividing the data on the 6V-71 engine by a factor of three. The daily duty-cycle weighted emissions presented in Table 18 for refrigerated car engines were derived from this source. Combining the refrigerated car daily emissions, the number of refrigerated cars per AQCR and the number of days per year in which the refrigerated cars are in service resulted in the annual emissions contributions of the secondary power sources. These values, expressed as tons per year are shown in Table 19 and constitute the final component of railroad emissions in each AQCR.

Table 17

Refrigerated Rail Car Emissions by Power Setting[1]

Percent of Rated Power @ Speed	Emissions (g/hour) HC	CO	NOx
95% @ 1200 rpm	14	1200	650
72% @ 1200 rpm	13	30	680
67% @ 800 rpm	10	30	580
20% @ 800 rpm	7	20	200

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[1] Extrapolated from data on a Detroit Diesel 6V-71 engine. "Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines," Hare and Springer, Southwest Research Institute, 1973.

Table 18

Refrigerated Rail Car Emissions

Emissions (pounds/day per refrigerated rail car) HC	CO	NOX
0.52	7.62	25.56

Table 19

Railroad Emissions in Five AQCRs

AQCR	Emissions (tons/year) HC	CO	NOx
Philadelphia:			
Line Haul	774	1,665	8,610
Switch	208	185	1,058
Secondary Power	15	226	758
Total	997	2,076	10,426
Chicago:			
Line Haul	6,278	13,499	69,820
Switch	1,690	1,502	8,587
Secondary Power	61	894	2,998
Total	8,029	15,895	81,405
St. Louis:			
Line Haul	986	2,120	10,963
Switch	266	237	1,354
Secondary Power	30	439	1,473
Total	1,282	2,796	13,790
Kansas City:			
Line Haul	1,075	2,312	11,960
Switch	290	258	1,473
Secondary Power	18	269	904
Total	1,383	2,839	14,337
Los Angeles:			
Line Haul	951	2,045	10,575
Switch	256	227	1,300
Secondary Power	23	333	1,116
Total	1,230	2,605	12,991

6.0 ENVIRONMENTAL IMPACT OF RAILROAD EMISSIONS

1 Non-Exhaust Emissions

1.1 Refueling Losses

Historically, fuel spillage and leakage have apparently en widespread and chronic railroad problems. While the timates of fuel losses vary significantly, the estimates ways point to substantial losses. The Stanford Research stitute (1977) estimated that about 10 percent of the ported fuel consumption of line-haul locomotives owned by ass I railroads (the largest railroads) was spilled or accounted for. Individual railroads have reported fuel illage and losses to be between 0.1 and 3.0 percent of the tal fuel purchased by Class I railroads (LMOA 1975). Based Southwest Research Institute (SwRI) figures, up to 367 llion gallons (9 percent of consumption) of diesel fuel or out 367 million dollars ($1/gal) have been spilled or accounted for each year.

To estimate only the amount of fuel spilled each year ring refueling, a conservative 2 percent (based on the LMOA ference) of the approximately 4 billion gallons purchased, is sumed. Based on these figures, a minimum of 80 million llons or 80 million dollars worth of fuel at present fuel ices, is spilled during refueling operations. This presents about $3,300 worth of fuel for each of the proximately 24,000 locomotives presently in service.

The causes of fuel losses during refueling operations pear to be well known. The two primary problems are: 1) mproperly attended manually operated fuel nozzles, and 2) poor aintenance of equipment. Because of the high delivery rates ring the refueling operation, 200-300 gallons per minute, ven difficulties of short duration can lead to a large volume ill. Additional losses occur when the locomotive fuel tanks re filled to excess or "topped off." In many cases, excess uel drains from the fill pipe when the cap is not replaced roperly or from the overflow vents when the train accelerates r rounds a curve.

Many of the accidental spills can be eliminated by the use f automatic shut-off refueling systems. Although some of hese systems are in-use, many railroads have apparently not nstalled them because of high initial costs and increased aintenance costs relative to those incurred for manual ystems. Apparently, the railroads have, on a historical asis, not found it cost effective to control the loss of fuel.

Even though the magnitude of refueling losses is very large, a preliminary investigation indicated this is not a significant source of air pollution. The high boiling point of diesel fuel precludes any large volume of gaseous hydrocarbons entering the atmosphere from the spilled fuel. The spilled fuel eventually, however, percolates into the ground. Even if these HC emissions were a significant contributor to air pollution, the railroad companies are now, or are expected in the future, to reduce refueling losses. As part of the Spill Prevention Control and Countermeasure Plans (SPCCP) mandated by the Federal Water Pollution Control Act (40 CFR 112), refueling terminals are being equipped with fuel recovery systems to prevent these liquid contaminants from reaching navigable waterways. At the same time, these measures eliminate much of the potential for fuel evaporation. The fuel recovery systems consist of concrete and metal drain pans under the rails at refueling points. After collection, the fuel is sent to a waste water treatment facility or is reused in a variety of ways, including use as a power plant or locomotive fuel. The economical reuse of this otherwise wasted resource helps offset the expenses of the SPCCP system.

The increasing cost of diesel fuel as well as possible shortages are expected to provide the strongest impetus for the elimination of refueling and spillage losses. This growing economic incentive in conjunction with the fact that proven technology exists for reducing this waste, is making it increasingly cost effective to install automatic refueling devices and provide proper maintenance. The cost-saving potential should be the most effective means of controlling emissions from this source.

6.2 Exhaust Emissions

6.2.1 Localized Effects

Areas which would typically experience the greatest air pollutant concentrations and longest exposure times to locomotive emissions are switch yards and those areas in close proximity to switchyards with high levels of railroad activity. The land use adjacent to 1,107 rail yards, or 27 percent of all rail yards, is classified as residential (FRA/ORD-76/304).

To assess the potential air quality impact of locomotive operations on a localized basis, the published literature was reviewed for information pertaining to this situation. No air quality monitoring in the vicinity of rail facilities was found, although analyses of the train crew's working environment do exist. Unfortunately, the majority of this work has been confined to determining exposure levels during worst case tunnel operations. Only one effort to model the effects of locomotive railyard operations on ambient air quality was found. A discussion of the relevant air quality monitoring and modeling studies follows.

6.2.1.1 Air Quality Monitoring

Two studies report nontunnel "background" concentrations (Thompson 1973 and Hobbs et al., 1977). The type of rail operation represented by Thompson's low exposure level (background concentration) is undefined in his report and since it may have been measured during line-haul and not switchyard service, it is not discussed further.

The analysis of localized, train-generated air contaminants by Hobbs et al., (1977) contains data collected in the cabs of switchyard locomotives. This study is summarized only to indicate whether the potential problem can be dismissed or if additional information is necessary. This is, of course, predicated on the assumption that the locomotive cab environment, during switchyard operations, represents a worst case condition because of its proximity to the engine exhaust and because air contaminants will be diluted to some extent as they are blown across the boundary of the rail facility. Therefore, if a problem does not exist in the cab of the locomotive, it is probable that a problem does not exist in the vicinity of concentrated rail operations.

Hobbs et al., (1977) continuously monitored the air in the cabs of three different switchyard locomotives for a total of approximately 19 hours. The 5-hour time weighted averages for several pollutants are shown in Table 20. If these data are regarded as the maximum 8-hour concentration for CO, the maximum 3-hour concentration for HC, and the annual averages for particulates and NOx (i.e., the worst possible case), three pollutants (CO, particulate, and NOx) are below the quality of the ambient air standards and one (HC) is above. (The HC standard is not health-based. It was promulgated because hydrocarbons are precursors to photochemical oxidants.) The high concentration of HC in the cab could be the result of contributions from several sources within the locomotive. Therefore, it may not be representative of the external environment (i.e., there is probably no relationship to the NAAQS welfare standard).

Unfortunately, Hobbs et al., (1977) did not include a discussion of the conditions under which the test values were recorded. This lack of information makes it difficult to determine if the locomotives being measured were in a worst, typical, or even a best case environment. The most important unknown is the ambient air quality in which the switch units

Table 20

Summary of Air Contaminant Levels in the Cab of Long-Hood, Forward Switch Yard Locomotives

Substance	5-Hour Time Weighted Average	NAAQS Health Effects	NAAQS Welfare Effects
Carbon Monoxide	0.26 ppm	9 ppm	
Particulates	10 ug/m^3	75 ug/m^3	
Nitrogen Dioxide	0.03 ppm		0.05 ppm
Hydrocarbons	3.12 ppm		0.24 ppm

were operating. If the ambient air quality had been measured, a direct analysis of the localized effects could have been performed.

6.2.1.2 Air Quality Modeling

The impact of diesel locomotive exhaust emissions from an Amtrak maintenance-of-way (MOW) base was modeled as part of an environmental impact statement which evaluated the facility's effect on localized air quality. An MOW base is a facility from which the right-of-way is maintained. It provides for employee parking and support facilities, office space, shops, interior and exterior security storage areas, and an external storage area for maintenance of equipment. The track area in the MOW is also used to store idling locomotives when they are not in-use along the right-of-way.

The ambient air quality modeling in the vicinity of the MOW was performed by DeLuew, Cather/Parsons and Associates for the Department of Transportation (DOT). In this analysis, Hanisch (1978) specifically modeled maximum 1-hour NO_2 pollutant concentrations only. In the model, it was assumed that three, 2-cycle, roots-blown, EMD switch locomotives (1,500 hp) were allowed to idle when parked end-to-end in the MOW (a normal occurrence).

For the worst case meteorological conditions (presumably the wind was blowing steadily in the direction of the most sensitive receptor), hourly concentrations of approximately 200 ug/m^3 or 0.10 ppm were predicted at about 85 meters (280 feet) downwind. There is, however, no national short-term NO_2 standard. EPA has considered the need for such a standard with consideration given to a maximum hourly NO_2 concentration of approximately 0.25 ppm. For the worst case modeled, the hourly NO_2 concentration was below the level which was considered by EPA.

6.2.2 Within AQCRs

Table 21 shows the estimated yearly railroad emissions, the total anthropogenic emissions inventories for 1983 (most recent year available) and the percentages of the totals contributed by railroads for the five Air Quality Control Regions which were studied.

The estimates of railroad contributions to the total anthropogenic emission inventory vary by AQCR, i.e., the estimated HC contributions varied from a low of 0.12 percent in Los Angeles to a high of 1.33 percent in Chicago, CO contributions varied between 0.06 percent in Los Angeles and 0.53 percent in Kansas City, and NOx contributions varied

Table 21

Railroad Emission, Total Anthropogenic Emissions and Percentage Contributions by Railroads for Five AQCR's

	Emissions (1000 tons/year)								
	HC			CO			NOx		
AQCR	Railroad	Total	%	Railroad	Total	%	Railroad	Total	%
Philadelphia	1.00	429.85	0.23	2.08	1,633.91	0.13	10.43	292.48	3.57
Chicago	8.03	603.27	1.33	15.90	2,228.03	0.07	81.41	551.07	14.77
St. Louis	1.28	251.05	0.50	2.80	932.69	0.30	13.79	356.11	3.87
Kansas City	1.38	128.21	1.08	2.84	532.18	0.53	14.34	162.19	8.84
Los Angeles	1.23	1,048.14	0.12	2.61	4,307.33	0.06	12.99	533.98	2.34

between 2.34 percent in Los Angeles and 14.77 percent in Chicago. The estimates suggest that railroads should be viewed as significant sources of NOx emissions in some AQCRs, HC emissions may be significant in some AQCRs while, along with CO, may be of little significance in other AQCRs.

Inspection of Tables 12 and 13 on the basis of locomotive throttle notch position, shows that the idle mode tended to be the single largest contributor of railroad hydrocarbon and carbon monoxide emissions. For switch and transfer locomotives the idle mode was also the largest contributor of NOx emissions. For line-haul locomotives, the idle mode was the third largest contributor of NOx emissions. After the idle mode, notch 8 tended to be the second major contributor of locomotive emissions. To place these observations in perspective, the individual percentile contributions of these operational modes were calculated and are presented in Table 22. The largest contribution to NOx emissions came from notch 8 operations and represented approximately 24 percent of the total railroad emissions of NOx. Idling locomotives contributed approximately 14 percent of total railroad NOx emissions in AQCRs. Idling locomotives were the largest operational mode contributors of hydrocarbon and carbon monoxide emissions at approximately 34 percent and 29 percent respectively. Notch-8 operation was the second largest contributor of carbon monoxide and hydrocarbon emissions at approximately 26 percent and 16 percent, respectively.

Table 22

Percentage of Total Railroad Emissions in AQCRs Contributed by Idle Mode and Notch-8 Operations[1]

	Percent of Total Emissions by Mode					
	Idle			Notch-8		
	HC	CO	NOx	HC	CO	NOx
Switch and Transfer Locomotives	12.3	5.0	3.8	1.5	1.5	1.3
Line-Haul Locomotives	22.2	24.4	10.3	14.4	24.8	23.1
Switch and Transfer plus Line-Haul Locomotives	34.5	29.4	14.1	15.9	26.3	24.4

1/ Calculated from emission rates shown in Tables 12, 13, 14, and 19.

7.0 POTENTIAL EMISSION REDUCTION TECHNIQUES

Procedures which have a theoretical potential* for reducing locomotive gaseous emissions fall into two general categories. These categories are modifications to the duty cycle and the application of emission control technology. The benefits which are projected for these categories are discussed in this chapter.

Since there was no data in the literature on either direct measurements of particulate emissions from locomotives or the effects of particulate control strategies on locomotive engines, quantification of potential particulate control was not attempted. Particulate control strategies presently under development by manufacturers of heavy-duty diesel truck and bus engines together with a reduction in the sulfur level of locomotive diesel fuel may, to greater or lesser extents, be applicable to locomotives.

7.1 Duty Cycle Modifications

7.1.1 Engine Shutdown When Not in Active Service

Historically, diesel locomotives have been allowed to idle when not in active service. These periods of standby idle are often extensive; they may routinely be as high as eight or more hours consecutively, with prolonged periods (48 hours or more) not being uncommon under certain conditions.

The railroad industry has historically found it more attractive to allow these diesel engines to idle rather than to shut them down. An idling locomotive engine is relatively warm and immediately available for service. When a cold locomotive engine is started, its large mass (30,000 to 50,000 lbs) dictates a lengthy warm-up period before maximum horsepower can be developed (up to two hours when the engine has completely cooled to an ambient temperature of 50° to 60°F). During most of the warm-up period, the locomotive is unavailable for use and could present a blockage on the section of track where the warm-up is occurring.

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* It should be carefully noted that some procedures which exhibit a theoretical potential for reducing locomotive emissions may not be practical for use. These procedures are, however, included in the discussion together with the factors influencing their impracticality.

In addition to the lengthy warm-up period required, other time-consuming and potentially expensive problems have been associated with starting a cold locomotive diesel engine (assuming that the ambient temperature is high enough to allow an engine start to be achieved). These problems are associated with the size of the engine and, to a certain extent, the design and maintenance of the engine. Coolant may leak past the cylinder liner to cylinder head seals into the cylinder(s) and, if it is not manually purged, could cause a hydraulic lock in the engine during cranking. This hydraulic lock in combination with the high inertia of the moving parts of the engine and the generator rotor will result in severe engine damage. Leaking of coolant past the cylinder liner to cylinder block seals would contaminate the engine oil. Contamination of the engine oil with a relatively large volume of water would cause bearing failures (leakage of a relatively small volume of water during engine shut-down can be tolerated because the water is evaporated when the oil is heated to operating temperature). During prolonged engine shutdown, lubrication oil drains back into the oil pan, thereby leaving many engine components unlubricated at start-up. This temporary oil starvation at start-up causes excessive wear rates during the period of inadequate lubrication and, with repeated occurrences, will result in engine damage. To prevent these problems, the historical practice has been to have trained maintenance personnel open cylinder test valves to drain any coolant from the cylinders, pre-lubricate, and manually turn the engine one or two revolutions before starting is attempted.

As a means of reducing fuel consumption, manufacturers have recently shown that many newer locomotives can be shut down with relative safety when the ambient temperature is 50°F or above. Protection against damage resulting from a hydraulic lock is achieved by providing a means whereby an extremely low cranking speed is used initially. If a hydraulic lock does not occur, normal cranking speed is then employed to start the engine. Should a hydraulic lock occur, it is rectified prior to the use of normal cranking speed by opening the cylinder test valves and draining the water.

At ambient temperatures below 50°F, starting of these large diesel engines is very difficult. At temperatures below 35°F starting is usually impossible. This characteristic of poor startability at low ambient temperatures is shared by all diesel engines. The problem of startability is addressed in car and truck diesel engines through the use of starting aides such as glow plugs in the combustion chambers or intake air preheaters. These technologies have not been used on diesel locomotive engines. Because of combustion chamber configuration and because of severe cylinder head design problems which would be associated with the application of glow plugs to locomotive engines (see Chapter 8), intake air preheating appears to offer the greatest potential for incorporation into new locomotive engines and appears to be the only approach with potential as a retrofit cold-start aid for in-use locomotives. Determination of the practicality of applying glow plugs or intake air preheating to new locomotives and retrofitting of intake air preheaters to older locomotives can only be made in cooperation with the manufacturers and users of the locomotives.

Current locomotive designs preclude any considerations of shut-down at ambient temperatures of 32°F and below because there is no provision for preventing freezing of the coolant. While the use of antifreeze in the cooling systems would appear to offer a solution for the control of coolant freezing, three problems are readily identifiable which will require resolution prior to the successful use of antifreeze and consequently prior to low temperature shutdown becoming practical. Two of these problems have already been identified, i.e., engine startability at temperatures below 50°F and coolant leakage. Leakage of even a small volume of coolant containing antifreeze into the oil can result in component failures. The need to prevent contamination of the oil with coolant is, therefore, substantially greater when antifreeze is employed. The third problem associated with the use of antifreeze in locomotives stems from the effects on engine cooling. Briefly, the addition of antifreeze to the engine cooling water decreases the rate of heat removal in the engine and the rate of heat rejection at the radiator. If space is available on the locomotive for a larger radiator, this segment of the problem can be resolved, but at some cost. It is not presently clear, however, what methods would be most suitable to increase the heat rejection rate in the engine.

If the problems of engine startability at relatively low ambient temperatures and coolant leakage can be overcome, engine shutdown at temperatures approaching 32°F may become practical.* If solutions to the problems associated with the use of antifreeze can be found, locomotive shutdown at temperatures lower than 32°F may become practical.

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* Cyclic starting, warming-up and shutting-down of locomotives is probably not practical as a method of reducing idle times and resolving cold starting problems because: 1) repeated thermal cycling tends to worsen the water leakage problem, 2) smoke and probably hydrocarbon emissions are high during engine warm-up, and 3) additional personnel would be required to perform this function thereby increasing costs.

Table 22, which was developed previously, shows the percentage contribution of locomotive idling emissions to the total railroad emissions for each type of locomotive based on historical operational practices. Estimates of reductions in emissions from locomotives through reductions in the time spent at idle can be developed by deriving modified duty cycles and the corresponding emissions. The factors which determine the amounts to which duty cycles can be modified are engine startability versus ambient temperature, operational considerations of the trains which limit the amount of shut-down which can be practiced and the effects of cold-start emissions following a shut-down. Three scenarios are readily identifiable for the relationship between engine shut-down and restart versus ambient temperature. These scenarios are: 1) that the engine can be started under essentially all ambient temperatures, 2) that antifreeze continues not to be used and, therefore, that the inclusion of starting aids is limited to those which are effective at 32°F and above, and 3) that engine startability is limited to 50°F and above.

Under the first scenario (startability is possible at all temperatures), practical considerations of train operation are assumed to limit shut-down to 60 percent of present idle time and that emissions during the cold-starts are equal to approximately 10 percent of daily idle emissions. Under this scenario, idle emissions would be reduced by approximately 50 percent. The resulting reductions in overall railroad emissions in AQCRs would be on the order of 17 percent for HC, 15 percent for CO and 7 percent for NOx.

Under the second scenario (engines can be shut-down at temperatures above 32°F) the theoretical maximum amount of engine shut-down can be estimated on a national annual basis from the number of days when the ambient temperature does not fall below 32°F. The theoretical maximum reduction in idle time with this constraint is approximately 40 percent.[18] If it is assumed that practical train operating constraints and cold start emissions reduce this value by 20 to 25 percent, the resulting projections for reductions in railroad emissions are on the order of 10 to 11 percent for HC, between 8 and 9 percent for CO and between 4 and 4 1/2 percent for NOx.

Under the third scenario (shut-down at 50°F and above) the reductions in emissions are estimated to about one-half of those estimated for the second scenario, i.e., reductions in HC, CO, and NOx emissions would be on the order of 5 percent, 4 percent, and 2 percent, respectively.

Not only do idling locomotives contribute to the pollutant burden in a region but they consume fuel while performing no useful work. While locomotive manufacturers and operators are already pursuing engine shut down to conserve fuel, the increasing cost of fuel should favorably dispose both the manufacturers and the operators to address the concept of maximizing locomotive shutdown when not in active service. It is presently not clear, however, what level of effort may be employed by manufacturers to address problems associated with engine shutdown and restart. It is equally not clear whether railroads would utilize locomotive shutdown capabilities if provided by manufacturers.

Table 23 summarizes the fuel consumption rates for an average switch and transfer locomotive and for an average line-haul locomotive as functions of throttle notch position and by duty cycle (these in-use locomotive weighted values were calculated using the same methodology as was used previously for emissions). In the case of switch and transfer locomotives, approximately 38 percent of the total daily fuel usage by these units is consumed in the idle mode. The comparable value for line-haul locomotives is approximately 12 percent when operating in an AQCR (i.e., on a 12 hour per day basis). Estimates of the monetary value of the fuel which could be saved through locomotive shut-down are presented in Chapter 8.

7.1.2 Limiting Use of Highest Power Settings When in Urban Areas

Eliminating the use of throttle notch positions 6, 7 and 8 in metropolitan areas may be a method of providing a measure of emissions reductions from this source (locomotives). The practicality of this approach has, however, not been established and it must be viewed as having a low potential for success. As a minimum, the following conditions would have to be met for this approach to be practical: 1) that the locomotives assigned to each train under present operating practices could perform the work required at reduced power settings when in urban areas, and 2) that train schedules would not be significantly affected. If these conditions can not be met, disruptions in train schedules could result and a net increase in emissions could result either from the addition of locomotives to each train so as to maintain schedules or from an increase in time for each trip. If the conditions could be met, the estimates of the effects on locomotive emissions are as follows. In the case of switch and transfer locomotives, the reductions would be very small because of the existing limited use of high throttle notch positions. For line-haul locomotives, the projected per locomotive effects of substituting throttle notch position 5 for the higher power settings are reductions of 11 percent, 30 percent and 22 percent for HC, CO and NOx, respectively.

Table 23

Locomotive Fuel Consumption - Average Values in AQCRs

Throttle Notch	Switch and Transfer Locomotive		Line-Haul Locomotive	
	#/hr	#/day[1/]	#/hr	#/day[2/]
Idle	24	444	38	269
1	48	81	68	57
2	85	143	148	107
3	117	112	263	189
4	216	104	369	266
5	285	68	570	205
6	364	44	662	238
7	453	54	865	311
8	545	131	1,040	624
Dynamic Brake	-	-	124	30
Total		1,181		2,296

1/ 24-hour/day duty cycle.
2/ 12-hour/day duty cycle in AQCRs.

Ignoring any small benefit attributable to switch and transfer locomotives, this change in the duty cycle, relative to the historical cycle, offers the potential for about an 8 to 9 percent reduction in HC emissions, between a 26 and 27 percent reduction in CO emissions and about an 18 percent reduction in NOx emissions from railroads in metropolitan areas.

7.1.3 Composite Effect of Duty Cycle Modifications

Adoption of both of the changes to the historical duty cycles (i.e., reductions in idle time and substitution of notch 5 for notch 6, 7, and 8 operations) would be projected to offer the potential for reducing railroad HC emissions by between 13 and 26 percent (the smaller reduction corresponds to 50°F shutdown capability and the larger reduction corresponds to a shutdown capability at all temperatures). Corresponding potential reductions in CO emissions range from 30 percent to 42 percent while reductions in NOx emissions may range from 20 to 25 percent.

7.2 Application of Emission Control Technology

In the area of exhaust emissions characteristics, large diesel engines used in locomotives tend to be similar to smaller diesel engines used in trucks and passenger cars. Generally, the control of exhaust emissions from diesel engines pose significant problems with respect to smoke (particulate material) and oxides of nitrogen, while posing lesser problems with respect to hydrocarbons. Because carbon monoxide emissions are inherently quite low, control of CO is not considered to be a problem.

The literature did not contain data on the effects of control techniques when applied to full-size locomotive engines. Work which had been performed to assess the effectiveness of control technologies on locomotive engines employed relatively smaller engines and the results necessitate an extrapolation to the full-size locomotive engine (Assessment of Control Technologies for Reducing Emissions from Locomotive Engines, 1973). It is also important to note that the engines tested were all 2-stroke units and that the data would therefore be most applicable to locomotives produced by EMD. Directionally, the data should be useful with 4-stroke engines (GE products) but quantification would be greatly in doubt.

Emission control techniques of general interest to diesel engines which were considered in the study were: 1) modification of fuel injection timing, 2) modification of injector design, 3) exhaust gas recirculation, 4) internal exhaust gas recirculation (reduced scavenging), and 5) water injection. Each of these techniques is discussed below.

Throughout these discussions, the effects will be expressed in terms of locomotive duty cycles as used in this study with the exception of smoke which could not be quantified in these terms because the lack of an appropriate data base. It must be remembered that the duty cycles do not include any changes which may recently have occurred to reduce engine idle time.

7.2.1 Modification of Injector Design

Results from testing with three types of injectors were reported. The types of injectors tested were: spherical valve, needle valve and low-sac. The older (at the time that testing was performed), spherical valve design was being replaced on in-use locomotives by the needle valve and low-sac designs. Low-sac injectors are presently standard equipment on EMD locomotives and are provided as replacement parts for older EMD locomotives. The reported relative effects of the three types of injectors were:

1. The low-sac injectors reduced hydrocarbon emissions relative to the needle valve type on the order of 50 percent for the switch and transfer duty cycle and about 15 percent for the line-haul duty cycle (low-sac injector technology was introduced by locomotive manufacturers as a method of reducing HC emissions).

2. Low-sac type injectors resulted in NOx emissions which were about 15 percent higher than those from the needle valve type injector on the switch and transfer duty cycle and about 30 percent higher on the line-haul duty cycle. Relative to the spherical injectors, the needle valve type was essentially equal on the switch and transfer duty cycle and about 20 percent better on the line-haul duty cycle.

3. Smoke opacity measurements were essentially equal for all injector types.

4. The low-sac injectors gave benefits of 20 to 25 percent in carbon monoxide emissions relative to the needle valve type of injector on both duty cycles.

5. It was not possible to identify any effects on the efficiency of fuel utilization associated with the different types of injectors.

7.2.2 Modification of Injection Timing (Timing Retard)

Directionally, the results of retarding injection timing (within reasonable limits) are to reduce oxides of nitrogen emissions, to increase smoke, to have little effect on hydrocarbon emissions and to tend to increase carbon monoxide.

The effect on the efficiency of fuel utilization (fuel consumed per unit of useful work performed) was not reported in the data. Some penalty can, however, be anticipated and can reasonably be expected to be on the order of 1-2 percent.

The effects of injection timing retard, based on the locomotive duty cycles, are summarized below:

1. NOx emissions could be reduced by 25 to 30 percent on both the line-haul locomotive duty cycle and switch and transfer locomotive duty cycle.

2. Smoke opacity would be increased by 50 to 100 percent throughout the speed/power range of the locomotive when needle type injectors were employed (old injector design). With recent design (at the time that the data were collected) low-sac injectors,* the increase in smoke emissions resulting from injection timing retard was under 50 percent. Derating the maximum power of the engines by 10 to 15 percent tended to alleviate the increased smoke levels. It is important to note that these data were expressed in terms of opacity and not in terms of the mass of particulate emitted (mass emission measurements were not performed).

3. Hydrocarbon emissions were generally unchanged as a result of injection timing retard. A reduction of between 1 and 4 percent may, however, be indicated.

4. On the switch and transfer locomotive duty cycle, carbon monoxide was almost unaffected (needle valve injectors were associated with a reduction of a few percent and low-sac injectors (newer design) were associated with an increase of a few percent). On the line-haul locomotive duty cycle, carbon monoxide would be projected to increase by approximately 20 percent as a result of retarded injection timing.

7.2.3 Exhaust Gas Recirculation

The referenced study investigated both cooled and uncooled exhaust gas recirculation (EGR). Because the data for cooled EGR were collected under laboratory conditions, the degree of cooling provided was not constrained as it would be on a locomotive. Those results were not judged, therefore, to be representative of the effects of cooled EGR in locomotive operation and are not included in this report. Application of uncooled EGR resulted in the following effects:

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* Low-sac injectors have been standardized for use on new EMD locomotives and are provided as replacement parts for older EMD locomotives.

1. Engine operation was unstable with exhaust gas recirculation, especially at the maximum EGR rate which was employed, i.e., 30 percent EGR level. Engine power was generally reduced as a result of the use of EGR. The amount of power loss was, however, not clearly quantified. The effects on emissions given below are based on a maximum EGR rate of 20 percent where engine operation was still relatively stable.

2. NOx emissions were decreased by approximately 30 percent on the switch and transfer duty cycle and by approximately 50 percent on the line-haul duty cycle.

3. Smoke opacity was increased by a factor of approximately two at low-power conditions and increased by a factor of six to seven at high-power conditions.

4. Twenty percent EGR rates had little effect on CO under the switch and transfer duty cycle conditions but increased CO by a factor of between two and one-half and five on the line-haul duty cycle, dependent upon the type of injector being used. The low-sac injectors which were introduced to reduce HC emissions, were associated with the greatest increase in CO.

5. Reductions in hydrocarbon emissions associated with the use of EGR were on the order of 25 to 50 percent on the switch and transfer duty cycle and on the order of 10 to 20 percent on the line-haul duty cycle.

6. Determination of the effects of EGR on the efficiency of fuel utilization could not be made because of insufficient data. The increases in CO and smoke emissions, are however, indicative of decreased efficiency in fuel utilization (a one percent penalty will be assumed).

7.2.4 Reduced Scavenging (Increased Internal Exhaust Gas Recirculation)

On the 2-stroke engine tested, this approach was accomplished by bleeding a portion of the intake air charge at the air box, i.e., reducing the amount of cylinder scavenging. A similar effect would be achieved on a 4-stroke engine by increasing valve overlap if very little overlap were presently used or by air bleed as was used on the 2-stroke engine. The reported results were as follows:

1. With an air bleed rate of approximately 35 percent, a reduction in power output, on the order of 10 to 20 percent was observed at the high power settings. Engine roughness was experienced at the higher air bleed rates investigative, i.e., at air bleed rates greater than 20 percent. The effects on

emissions as summarized below are, therefore, limited to air bleed rates of 20 percent.

2. NOx emissions on the switch and transfer duty cycle were reduced approximately 15 percent and on the line-haul duty cycle by between 10 and 15 percent.

3. Smoke opacity increased on the order of 50 percent at low power and up to 300 percent at maximum power.

4. Hydrocarbon emissions were little changed on both duty cycles when the low-sac injectors were utilized. Needle valve injectors in conjunction with the air bleed resulted in approximately a 40 percent reduction in HC emissions on the switch and transfer duty cycle, and approximately a 20 percent reduction on the line-haul duty cycle.

5. Carbon monoxide emissions were reported to decrease by 30 percent on the switch and transfer duty cycle and to increase by 30 percent on the line-haul duty cycle when needle valve injectors were in-use. The results with the low-sac injectors were a 15 percent increase in CO on the switch and transfer duty cycle and a factor of three increase on the line-haul duty cycle.

6. The effects on the efficiency of fuel utilization could not be determined from the data. The increases in CO and smoke emissions which were observed are, however, indicative of reduced combustion efficiency and probably reduced fuel economy (a one percent penalty will be assumed).

7.2.5 Water Injection

Application of water injection to locomotives will pose such practical in-use problems as: 1) freezing in cold weather, 2) corrosion in the water injection system and possibly in the engine, 3) storage capacity on the locomotive for the large volume of water required (75 to 100 percent of fuel tank volume), and 4) the availability of water of suitable purity (contaminants in the water will result in build-up of deposits in the water delivery system and in the engine). The reported effects on emissions of water injection rates equal to 75 percent of fuel flow rates were as follows:

1. NOx emissions were reduced between 15 and 20 percent on both duty cycles with both the low-sac injectors and the needle valve injectors.

2. There was little overall effect on smoke opacity.

3. Hydrocarbon emissions were decreased (needle valve injectors) by about 50 percent on the switch and transfer duty cycle and by 20 percent on the line-haul duty cycle. With the low-sac injectors, hydrocarbon emissions increased between five and 15 percent.

4. Carbon monoxide decreased by approximately 5 percent on both duty cycles with the low-sac injectors and by an equal amount on the line-haul duty cycle when the needle valve injectors were used. Carbon monoxide increased by 25 percent on the switch and transfer duty cycle when the needle valve injectors were used.

5. The report indicated a slight improvement in power and, as with the other emission control techniques, the effect on the efficiency of fuel utilization could not be determined (no fuel economy penalty is assumed).

In summary, the results of the study show similar trends for locomotive diesel engines as are observed with other diesel engines, i.e., control techniques which benefit one pollutant, for example, NOx, often result in an increase in another pollutant, for example, smoke (particulate). It is worth noting, however, that progress is being made by other diesel engine manufacturers, e.g., those making heavy-duty diesel truck engines, in controlling the trade-off between these pollutants. It is not unreasonable to expect that similar benefits could be realized in the case of locomotive engines.

8.0 COST AND COST-EFFECTIVENESS ESTIMATES

Following the approach used in the previous chapter, estimates of costs (1984 dollars) are divided into two general types of control procedure. The costs are those associated with changes in operating practice (duty-cycle modifications) and costs associated with the application of emission control technology. The cost-effectiveness estimates are presented in the section which follows the cost estimates.

Estimates of costs shown in this chapter were developed from meetings between EPA and locomotive manufacturers and from costs associated with emission controls used on automobiles and trucks. While both manufacturers of locomotives cooperated with EPA in developing a general understanding of the effects of adding emission control systems to locomotives, neither felt that reliable estimates of costs could be developed at this time. One basis for their uncertainty was the lack of detailed design information associated with the application of emission controls to locomotives and consequently the unavailability of a basis for the development of accurate costs. The second basis for the uncertainty is the significant difference which exists between the high volume manufacturing processes used on automobiles and trucks and the very low volume manufacturing processes used on locomotives. Extrapolations of the costs of locomotive components from costs associated with automobiles and trucks are, therefore, subject to substantial uncertainty.

For the reasons given above, it is very important to stress that the costs shown in this chapter should be viewed as first order approximations which are subject to change.

8.1 Duty Cycle Modifications

8.1.1 Engine Shutdown When Not in Active Service

Estimates of the costs of changes to locomotives which may be required to achieve engine shutdown can be grouped into three categories. In decreasing order of magnitude the costs would be associated with: 1) engine shutdown capability at temperatures below freezing, 2) engine shutdown capabilities at temperatures just above freezing and 3) engine shutdown capabilities at 50°F and higher.

Problems requiring resolution for engine shutdown at temperatures below freezing are: engine startability, the need to improve heat dissipation in the engine and the radiator as a result of the use of antifreeze, prevention of fuel "waxing,"* limiting cold start emissions, provision for adequate lubrication at startup, provision of lubricants which perform adequately when both hot and cold, elimination of coolant leakage into the crankcase and cylinders if antifreeze is used and provision for removal of any coolant which may leak into the cylinders where antifreeze is used. With engine shutdown at temperatures just above freezing, the problems associated with the use of antifreeze are avoided and the severity of the fuel waxing and lubrication problems are reduced. With shutdown limited to 50°F or higher, the problems are reduced to the control of cold start emissions and coolant leakage and to a lesser extent provision for adequate lubrication immediately following start up.

Potential methods of resolving the problems and the associated costs are addressed in the following paragraphs. The total cost for each of the categories are developed by summing the costs of appropriate remedial actions. Credits for anticipated fuel savings are incorporated for each category.

8.1.1.1 Engine Startability

Ignition of the fuel in a diesel engine is achieved by compressive heating of the air in the cylinders to a temperature which is sufficiently high to cause the fuel to ignite. Two factors are primary contributors to the problem of starting a cold diesel engine. The first factor is the relatively low temperature of the air after compression because of the low initial temperature of the air. The second factor is the cooling of the air during compression by the cold surfaces of the cylinder wall and combustion chamber. In combination, these two factors play the critical role in establishing the ambient temperature below which a given diesel engine will not start without the use of some form of starting aid.

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* Fuel "waxing" - diesel fuel contains some wax which solidifies at low temperatures and prevents the fuel from flowing. When the engine is in operation, the quantity of fuel delivered to the engine is greater than that required to operate the engine. The excess fuel is returned to the fuel tank. As the fuel flows through the fuel distribution lines on the engine, it is warmed and the warm excess fuel prevents fuel waxing in the tank and supply lines.

The most readily identifiable methods of improving the startability of diesel engines are; the introduction of electrical heating elements into the combustion chamber(s) (glow plugs), heating of the air before it enters the engine, use of a readily startable auxiliary engine to rapidly crank the main engine for a prolonged period of time coupled with heating of the intake air by the exhaust gases of the auxiliary engine, the use of an auxiliary starting fuel and the use of a starting fluid which is introduced into the intake air.

Functionally, glow plugs provide a hot-spot in the combustion chamber as well as some heating of the metal which forms the surface of the combustion chamber and some of the air in the chamber. Glow plugs are the standardized method whereby starting is achieved in the relatively small, indirect injection (IDI) diesel engines used in passenger cars. Glow plugs are seldom if ever used in the relatively larger, direct injection (DI) diesel engines used in heavy-duty trucks. The reason for this difference in the application of glow plugs is attributable primarily to the differences in the combustion chambers and to a lesser extent to the differences in engine size. In an IDI engine, the combustion chamber consists of two interconnected chambers with the fuel being injected into only one of the chambers. As a result, heating by a glow plug can be concentrated in the section of the chamber where fuel injection and consequently ignition occurs. In a DI engine, a single chamber is employed and as a result, the problem of providing sufficient and appropriately located heating is substantially greater than is the case for an IDI engine. Because of the differences in combustion chamber configuration, significantly less electrical energy is required for the successful heating and consequently starting of an IDI than would be required in a DI engine of comparable size. In addition, air which is warmed by the glow plug tends to be retained in the pre-chamber of the IDI engine during cranking while the air in the cylinders of the DI engine tends to be expelled during cranking. Locomotive engines are of the DI type with individual cylinder volumes which are between four and six times larger than those in heavy-duty truck engines. As a result of these factors, it is reasonable to expect that multiple glow plugs would be required in each cylinder of a locomotive engine so as to achieve the necessary heating. It is also reasonable to expect that each glow plug would be significantly larger than those used in passenger car diesel engines. A very substantial increase in the size of locomotive batteries would result from the use of glow plugs.

The tasks required for the application of glow plugs (the first option) to locomotive engines are the development of a new cylinder head design that would accommodate the glow plugs while retaining other necessary characteristics, provision for an adequate electrical energy storage system and an electrical wiring and control system interconnecting the glow plugs and the batteries.

Redesign of the cylinder heads to accommodate the use of glow plugs is expected to be very difficult. The reasons are that space allocated for the application of glow plugs must come from that presently allocated to cylinder head cooling and that the use of four valves per cylinder (existing design practice necessary to facilitate the high power output required) dictates glow plug placement in relatively unfavorable operational positions. Any reduction in either cooling capability or the size or number of valves will translate into an unacceptable reduction in the power of the engine. Because of the severity of the anticipated problems, the cost to each of the two locomotive builders for developing new cylinder heads is projected to be between $1,000,000 and $1,500,000. Recovery of these costs over five years with total yearly locomotive production of 1,200 units results in a per locomotive cost of between $340 and $500. Increased manufacturing costs per cylinder head would be in the range of $30 to $40. Locomotive engines employ a separate cylinder head for each cylinder and the majority of engines sold are 16 cylinder units (8, 12, 16 and 20 cylinder engines are available). On a per locomotive basis the manufacturing costs for the redesigned cylinder heads are, therefore, expected to be between $480 and $640. On a per cylinder head basis, the redesign and manufacturing costs equal between $50 and $70. These costs are between six percent and ten percent of the present price ($700-$800) of a replacement cylinder head.

The next cost component of the glow plug assisted starting approach to resolving low temperature startability is the cost of the glow plugs. Using the price of a replacement glow plug for a passenger car diesel ($20) as a guide, the cost of a glow plug for a locomotive engine is projected to be between $30 and $40. The higher cost relative to the passenger car unit results from the size increase (heating capacity) and low production volume of the locomotive units. If two glow plugs per cylinder can perform the necessary function, the per locomotive cost would be between $960 and $1,280. The per locomotive cost could increase to between $1,920 and $2,560 if four glow plugs were required per cylinder.

The remaining cost components of the glow plug assisted starting system would come from the increase in the size of the battery and the starter and from the electrical wiring and controls which would interconnect the battery and the glow plugs. A two fold increase in battery size is projected so as to provide an adequate energy supply for the glow plugs as well as the increase in engine cranking load which occurs at low temperatures. The price of the batteries which are presently used on locomotives is between $3,500 and $5,500. This price, plus an additional $100 for enlargement of the battery box is used to represent the cost for the increase in battery size. The price of a starter for a locomotive engine is approximately $1,000 (two are used). This price can be expected to increase by about 15 percent because of the increase in power necessary to crank the engine at low ambient temperatures. The incremental cost increase for the starter is, therefore, estimated to be about $300. The wiring harness for transmitting the energy from the batteries to the glow plugs, its locating parts and the system for automatically controlling the supply of energy to the glow plugs could cost between $300 and $500. The first cost of the glow plug assisted starting approach is the sum of the costs of the component parts and is projected to be in the range of $5,980 to $10,100.

Over the lifetime of the locomotive (assumed to be 15 years) it is reasonable to expect that replacement batteries will be purchased twice and that 25 percent of the glow plugs will require replacement. The discounted cost of these components would be between $4,200 and $6,900 including a labor cost for replacement of the defective components.

The second procedure which has been identified as a potential starting aid is preheating of the intake air. Design and development costs for this approach should be less than those for a new cylinder head. A per locomotive cost of between $100 and $200 is used assuming a level of effort which is about one-third that required for a cylinder head redesign.

The first set of components of this system would be the heating components which would consist of a fuel atomizer, fuel pump, combustion air blower, ignition system, combustion chamber and electrical supply, assuming that diesel is the fuel used in the heater. The second set of components of the system would consist of the heat delivery unit which could take more than one form. If the intake air preheater was mounted between the engine air filter and the turbocharger with its hot combustion gases being mixed with the air entering the engine, a relatively simple piping connection would form the heat delivery unit. A second method of heat delivery would be to mount the heating unit on the intake manifold downstream of the turbocharger and the intercooler with direct mixing of the hot combustion products and the intake air. This method of installation would require a relatively minor modification of the intake manifold and a one-way valve to prevent the loss of pressurized intake air during engine operation. The third method of supplying heat to the intake air would be by the use of a heat exchanger located either before the turbocharger or after the intercooler. While the use of a heat exchanger would be the most complex and costly approach of the three, it would remove problems caused by water condensation, intake air dilution and the build up of deposits in the engine intake system associated with the other approaches. The heat exchanger would have to be relatively large so as to minimize flow restrictions in the engine intake air system.

The cost of the heating components of the intake air heating system can reasonably be expected to be between $1,000 and $1,500 per locomotive. The cost of the heat delivery components using a heat exchanger is projected to be between $2,000 and $3,000 per locomotive and include the heat exchanger cost, the incremental cost for the redesigned intake manifold and an exhaust pipe for the heater. In addition to the cost of the intake air heating system, provision would have to be made for additional battery capacity so as to effectively crank the engine at low ambient temperatures. This additional battery capacity is expected to necessitate about a 50 percent increase in the size of the present batteries. This incremental cost is projected to be between $1,800 and $2,800 including $50 for a larger battery box and retaining hardware. The incremental cost for the starter would be the same as that associated with the use of glow plugs and is approximately $300. The cost of the intake air heating system is, therefore, projected to be between $5,200 and $7,800.

Lifetime discounted costs for battery replacement and maintenance of the heater system are estimated to be between $3,000 and $4,000.

The third method which was identified as a potential method for achieving starting of a cold locomotive diesel engine was the use of a readily startable auxiliary engine.* With this approach, achieving the required temperature of the air in the cylinders at the end of compression would be obtained by two paths. One path would be the heating of the air entering the main locomotive engine by the hot exhaust gases of the auxiliary engine. The other path would be the heating of the walls of the combustion chamber by the heat of compression through prolonged cranking of the main engine prior

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* It is questionable whether space is available in a locomotive for the auxiliary engine and associated hardware. The cost estimate for this approach to achieving low temperature startability is, however, based on the assumption that space can be made available. If space cannot be made available for the auxiliary engine within existing locomotive overall dimensions, use of an auxiliary starting engine will be precluded because of size constraints which are detailed in Section 8.2.5.

to the introduction of fuel. The components required for this approach are the auxiliary engine, speed reduction gearing between the auxiliary engine and the main locomotive engine, a means for coupling and decoupling between the two engines and a heat exchanger in the intake system of the main engine. The cost of the auxiliary engine, reduction gearing and engine-to-engine coupling is projected to be in the $5,000 to $7,000 range. The cost of the heat exchanger and the changes to the intake manifold would be similar to those for the preheater approach and would be between $2,000 and $3,000 per locomotive. On a per locomotive basis, the development costs would be similar to those associated with intake air preheating, i.e., between $100 and $200. If the use of an auxiliary engine for starting was viewed as a complete changeover from the use of an electric starter, these costs could be reduced by the cost of the electric starter ($2,000) plus a reduction in battery size by a factor of two to three. The cost savings in batteries could, therefore, be between $1,500 and $3,500. The incremental cost increase for an auxiliary engine for starting of the main engine is developed by combining the sum of the component costs and savings and is projected to be between $1,600 and $6,700. Lifetime discounted cost for maintenance of the auxiliary engine and drive systems should be between $500 to $1,000.

The fourth method which was identified for enhancing startability at low temperatures is the use of an auxiliary starting fuel which will ignite more readily than the primary fuel. The changes to the locomotive which would be required with this approach are the addition of a fuel tank for the auxiliary fuel, a system for purging the primary fuel from the injection system prior to engine shutdown and an increase in battery and starter size. The cost of an auxiliary fuel tank and the addition of a fuel selector valve to the fuel delivery line would not be large if space were available on the locomotive for the fuel tank. Assuming that space is available for a relatively small auxiliary fuel tank, the cost should not exceed $500. If space is not available for the auxiliary fuel tank, this approach for achieving enhanced engine startability may not be a viable option because locomotives are already at the weight and length limits imposed by track constraints i.e., locomotives cannot be enlarged to provide space for the auxiliary fuel tank. The incremental cost for the larger batteries and starter would be equal to that of the intake air preheat system; i.e., about $2,100 to $3,100. The total cost of the auxiliary fuel approach is projected to be about $2,600 to $3,600. Maintenance and battery replacement costs should be equal to those for an intake air preheating system, i.e., $3000 to $4000. While the cost of this approach is relatively low, its effectiveness as a starting aid is also low relative to the three procedures for which cost estimates have previously been developed. It is unlikely, therefore, that this approach would be employed where reliable starting was required at temperatures much below freezing.

The final approach for improving startability is that which is presently employed on some engines at approximately 50°F and for all engines at temperatures just below 50°F. This approach is the manual introduction of a small amount of ether into the intake system just prior to cranking of the engine. While the cost of this approach is minimal, it cannot be considered as a viable starting aid at temperatures below 40°F to 45°F.

Of the five methods for achieving low temperature starting of locomotive engines, two (glow plugs and intake air heating) presently appear to offer the greatest potential for use. Because of the anticipated problems associated with the application of glow plugs and because of the potential cold start emission control benefits of intake air preheating, this is the procedure which would probably be employed.

The estimates of the costs for the types of starting aides which have been considered are summarized in Table 24 for ease of reference.

8.1.1.2 Use of Antifreeze and Control of Fuel Waxing

Once an ability to start locomotives at low ambient temperatures is in place the need arises for the prevention of freezing of the coolant and fuel waxing during engine shutdown. Freezing of the coolant can be prevented by the use of the appropriate quantity of antifreeze. Use of antifreeze leads, however, to a reduction in the rate of heat dissipation at the radiators and from the walls of the combustion chambers and cylinders to the coolant.

Increasing the heat dissipation at the radiator can be achieved by the use of a larger radiator. The required increase in radiator size is expected to be on the order of 15 to 20 percent. The incremental cost increase for the radiator enlargement is projected to be between $1,000 and $1,500 based on existing radiator prices of between $10,000 and $12,000. This cost increase is based on the assumption that there will be no change in the existing fans and fan drives for moving air over the radiator. Obtaining the necessary space in the locomotive for the larger radiator is expected, however, to pose a problem. The cost of modifications to locomotives to secure the necessary space could range from $1,000 to $5,000 per locomotive and would depend upon the extent of the changes required.

Table 24

Summary of Costs: Engine Starting Aides

Starting Aide	Cost per Locomotive ($) First	Maintenance	Applicability
Glow plugs			All temperatures
Cylinder head and glow plugs	1,780-3,700	--	
Battery, Starter, Wiring	4,200-6,400	--	
Replacement batteries and glow plugs	--	4,200-6,900	
Total	5,980-10,100	4,200-6,900	
Intake Air Preheat			All temperatures
Heater	3,100-4,700	--	
Battery, Starter	2,100-3,100	--	
Replacement batteries and heater maintenance	--	3,000-4,000	
Total	5,200-7,800	3,000-4,000	
Auxiliary Engine			All temperatures
Engine, Drive, Heat exchanger	7,100-10,200	--	
Starter, Battery	(5,500-3,500)	--	
Maintenance	--	500-1,000	
Total	1,600-6,700	500-1,000	
Auxiliary Fuel			Above freezing
Tank, Plumbing	500	--	
Battery, Starter	2,100-3,100	3,000-4,000	
Total	2,600-3,600	3,000-4,000	
Ether	0	0	Above 40°to 45°F

It is not fully apparent how heat dissipation to the coolant could be adequately increased in the combustion chamber and cylinder liner regions of the engine without a major and very costly engine redesign. The most direct method for increasing heat dissipation to the coolant would be by an increase in the surface area of the engine components which are in contact with the coolant through the addition of fins or spines. There is little if any potential for increasing heat dissipation to the coolant in the cylinder head by this method because spines are already employed in the design. Increasing the surface area of the cylinder liner which is in contact with the coolant through the addition of fins or spines does not appear to be possible without a major engine redesign because of the present inability to insert the liners into the engine if fins or spines are employed. Increasing the rate of flow of the coolant through the engine may be a method for resolving the cooling problem. There is, however, no data to support the validity of this approach.

A second area where significant uncertainty exists with respect to methods of resolving identifiable problems is that of achieving control over coolant leakage. Locomotive manufacturers indicate that changes have recently been made to the engines which reduce the potential for coolant leakage into the crankcase and into the cylinders. These changes do not, however, provide the degree of confidence for the control of coolant leakage which would be required when antifreeze is used in the coolant. Because of the high cost of repairing an engine damaged by lubricant contamination as a result of leakage of antifreeze into the crankcase (an estimate of $50,000 to cover disassembly and cleaning followed by rebuilding with new cylinders, pistons, crankshaft, and bearings was provided by a manufacturer) and the time that the locomotive would be out of service for repairs, every effort can be expected to be made to prevent this type of leak.

If a major redesign were necessary, the cost can reasonably be expected to be between five and ten times that which was estimated for the redesign of a cylinder head; i.e., from a low of $10,000,000 to a high of $30,000,000 for the two manufacturers. Allowing for an increase in manufacturing cost associated with the redesign, the cost increase per locomotive can reasonably be expected to be in the range of $3,000 to $6,000.

The first cost increase attributed to the use of antifreeze in locomotive engines is the sum of the costs of the engine redesign, radiator enlargement and the cost of the antifreeze. These costs total to between $5,300 and $12,800 and include 200 gallons of antifreeze at $1.50 per gallon. Over the life of the locomotive, the discounted cost for ntifreeze for cooling system makeup and coolant changes would e approximately $2,500.

Problems of fuel waxing may be controlled either by the se of a fuel which will not exhibit a waxing problem at revailing ambient temperatures or by maintaining the fuel uring shut-down at a temperature sufficiently high to prevent he formation of wax crystals. Changing from the grade of iesel fuel which is presently used in locomotives to a grade hich would not exhibit the problem of waxing until a very low mbient temperature was reached is not considered to be a otally viable solution. At a minimum, the reasons for the ndesirability of this approach are twofold. First, fuel roducers would have to incorporate a portion of the fuel resently produced for such uses as jet aircraft into the iesel fuel for locomotives. This change in the locomotive uel blend could result in problems of adequate availability of ther fuel types. Second, the price of the fuel would be igher than that of presently used locomotive fuel. Assuming hat the price penalty would be five percent (i.e., 5 cents per allon) applicable to the fuel consumed during the coldest eriods of the year, i.e., about one-third of the fuel used by he railroads, the annual increase in fuel cost would be about 67 million (present annual consumption of about four billion allons of fuel at $1 per gallon) or about $2,800 per locomotive per year (discounted cost of approximately $22,200 ver a 15 year life).

Maintaining either all or part of the fuel at a temperature above that at which waxing would occur could be achieved by: 1) the addition of a fuel heater, 2) insulating the fuel tank to reduce the rate of cooling of the fuel and the amount of energy supplied by the fuel heater, and 3) the provision of a fuel drain back system which would remove all fuel from unheated regions of the fuel delivery system (fuel supply pump, filters, distribution and return lines). An electric fuel heater powered by the locomotive battery may be practical if the duration of each engine shut down was limited to between 8 to 12 hours and if only a small fraction of the total fuel volume of 3,000 gallons was warmed. With this approach, rewarming of the majority of the fuel could be achieved by piping engine coolant through the fuel tank once the engine had started and warm-up was underway. Provision for fuel heating under longer periods of engine shut down would require the use of an external burner system to prevent excessive discharge of the batteries. The cost of the electrical fuel heater approach is projected to be in the range of $500 to $1,000 to cover the heater, its controls, partitioning of the fuel tank, fuel drain back system and provision for heating the main fuel tank by engine coolant. The cost of a burner system would be in the range of $1,000 to

$2,000 for the burner, its fuel and air delivery systems, its controls and the fuel drain back system.

The costs associated with the use of antifreeze and the control of fuel waxing are summarized in Table 25.

8.1.1.3 Cold Start Emissions

Three emission species can pose problems with respect to their emission rate during diesel engine warm up following a start from low ambient temperatures. The emission species are smoke (particulate material), carbon monoxide and hydrocarbons. Primarily, poor combustion in a cold diesel engine is caused by low air temperatures at the end of compression which results in the failure of some of the fuel to ignite and by flame quenching prior to the completion of combustion for the remainder of the fuel. Because the problem of elevated emission rates following a cold start is primarily the result of low temperatures in the combustion chamber, pre-heating of the intake air, the fuel and reductions in the time required for total engine warm-up would tend to reduce these emissions. As was stated previously, the use of an intake air preheater is probably the most viable approach for enhancing cold engine startability. While this approach appears to offer the most reliable method for achieving a cold start, it also offers a method of reducing cold start emissions. Operation of the intake air preheater both before engine cranking is initiated and for some time after the engine has started would tend to reduce cold start emissions. Heating of the fuel by the intake air preheater before engine starting and during engine warm up would also tend to reduce cold start emissions. The cost of adding a fuel pre-heating element to the intake air preheater should not exceed a couple of hundred dollars for the heat exchanger and the necessary piping and valves to divert the fuel to the preheater during start up. Reducing the time for total engine warm-up is the third temperature related method for reducing cold start emissions. This could be achieved by the introduction of a thermostat* or similar method of isolating the coolant in the engine from the remainder of the coolant in the system. This coolant isolation would limit the volume of coolant which has to be warmed during engine warm up and would result in some reduction in warmup time. The per locomotive cost for the changes to the cooling system necessary to achieve a reduction

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* One locomotive manufacturer expressed concern with respect to the effects on railroad operations of a thermostat failure. The concern expressed was for the blockage of the tracks because the locomotive would become inoperable when a thermostat failed in the closed position.

Table 25

Summary of Costs:
Use of Antifreeze and Fuel Waxing Control

System	Cost Per Locomotive ($) First	 Maintenance	Fuel
Use of antifreeze			
Radiator	1,000-1,500	0	0
Space Modifications	1,000-5,000	0	0
Cylinder Redesign	3,000-6,000	0	0
Antifreeze	300	2,500	0
Total	5,300-12,800	2500	0
Use of different fuel blend	0	0	22,200
Fuel Heating			
Electrical	500-1,000	0	0
Auxiliary heater	1,000-2,000	0	0

in engine warmup time is expected to be on the order of $500 to $1,000. Assuming the use of intake air preheating for engine startability, the incremental cost of these approaches to reducing cold start emissions is projected to be between $700 and $1,200 per locomotive.

8.1.1.4 Lubrication Changes

Two changes in engine lubrication are expected to be necessary as part of any effort to increase the amount of engine shut down which can be practiced. These changes are addressed below.

An accelerated rate of engine wear is a problem with all engines during cranking and immediately after starting because of poor lubrication during this period. On engines where the desired period of useful operation is very long; e.g., locomotive engines, high wear rates associated with engine starting can be a significant problem especially when the number of cold starts is to be increased because of an increase in the number of engine shutdowns. Cold start wear rates may be reduced by the addition of an electrically driven auxiliary oil pump which would deliver lubricant to all parts of the engine prior to cranking. The cost of adding this system (oil pickup, pump, drive motor, plunging and check valve) would be on the order of $500 to $1,000 per locomotive.

The second change in engine lubrication which can reasonably be expected to be required is the need to use an oil which will flow when cold and which will also provide good lubrication when hot. Oils of this type are used almost exclusively in automobiles and are known as multi-viscosity oils; i.e., the oil exhibits the characteristics of a low viscosity oil when cold and of a high viscosity oil when hot. Availability of multi-viscosity oils for diesel locomotive engines is not expected to be an insurmountable problem. Some increase in the cost of multi-viscosity oils relative to the oils which are presently used is, however, anticipated. On the basis of a cost differential of 20 percent between the two types of oils,* a cost of $3 per gallon for oils which are presently used and a lifetime oil usage of 65,000 gallons to 70,000 gallons for initial oilfill, oil changes and make up oil, the projected cost increase is between $39,000 and $42,000 over the 15 year locomotive lifetime. As a discounted cost, these values would represent a cost of between $21,000 and $22,000.

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* Cost differential is based upon the difference of about 20 percent which currently exists in the automotive market for these oils (at discount outlets).

A summary of the costs of reducing cold-start emissions and in lubrication changes is given in Table 26.

8.1.1.5 Fuel Savings from Engine Shutdown

Under the three temperature dependent engine shutdown scenarios, the estimated reductions in idle time are 60 percent, 40 percent and 20 percent for shutdown capability under all temperatures, just above 32°F and at 50°F and above, respectively. Combining these values with the idle fuel consumptions shown in Table 23, weighted by the ratio of line-haul to switch locomotives* and allowing for fuel used during cold starts (assumed to be 10 percent of fuel saved by shutdown) results in annual fuel savings per locomotive of approximately 8,000 gallons, 5,300 gallons and 2,700 gallons for each scenario. With a fuel cost of $1 per gallon, a locomotive life of 15 years and a discount rate of 10 percent, the lifetime savings in fuel are approximately $63,500, $42,000 and $21,400, respectively.

8.1.1.6 Composite Costs for Engine Shutdown

As was previously indicated, three levels of temperature related costs can be associated with engine shutdown when the locomotive is not in service. These costs are dependent on the severity of the problems associated with shutdown and restart and are based on the ambient temperature at which shutdown is desired. The three temperature scenarios are: 1) shutdown capability at temperatures below freezing, 2) shutdown capabilities at temperatures just above freezing, and 3) shutdown capabilities at approximately 50°F and above.

To achieve shutdown capabilities at temperatures below freezing, costs would accrue from the provisions for engine startability at very low temperatures, use of antifreeze, control of fuel waxing, reductions in cold start emissions and changes in lubrication. The cumulative cost for this approach is expected to be between $38,700 and $53,300 assuming that intake air preheating would be employed. If other approaches to achieving low temperature startability were to be employed, the cumulative cost could range between $32,600 and $58,500. The lifetime savings resulting from reduced fuel usage is estimated to be about $63,500.

With engine shutdown constrained to temperatures just above freezing, it is again probable that the intake air

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* The ratio is approximately 3.93 line-haul locomotives per switch locomotive as derived from the number of locomotives shown in Table 14.

Table 26

Summary of Costs: Reducing Cold Start Emissions and Lubrication Changes

	Cost Per Locomotive ($)	
	First	Maintenance
Reducing cold start emissions		
Fuel Preheater	200	0
Thermostatic Control	500-1,000	0
Total	700-1,200	0
Lubrication changes		
Auxiliary Pump	500-1,000	0
Improved Oils	0	21,000-22,000
Total	500-1,000	21,000-22,000

preheater would be preferred because of its ability to provide engine startability as well as reducing cold start emissions, that changes in lubrication would be used and that the use of antifreeze would be avoided. The cumulative cost for this approach is projected to be between $30,900 and $38,000. The lifetime savings in fuel is projected to be about $42,000.

Locomotive manufacturers consider 50°F as being the lower limit of the temperature region in which new locomotives can be reliably started. There are, therefore, no new costs attributable to engine shutdown when temperatures are 50° and above. The lifetime savings in fuel are projected to be about $21,400.

8.1.2 Restricted Use of High Power Settings in Urban Areas

The assumption underlying this concept for the reduction of emissions from line-haul locomotives is that the power required to propel the train up grades and at scheduled speeds when the train is outside of urban areas exceeds similar power requirements when the train is in urban areas. It is also assumed that a reduction in the speed of the train when in urban areas would not be large enough to significantly impact either the train schedules or the total time of locomotive operation in urban areas.

If the underlying assumptions are correct, small cost increases due to small schedule changes and increases in train operator working hours can be expected to be either partially or wholly recovered through savings in fuel usage.

If the underlying assumptions are in error, the costs could be substantial and the net effect on railroad emissions could be negative; i.e., emissions could actually be increased. The potential for significant costs stems from the reduction in the effectiveness of utilization of existing railroad facilities (track, locomotives, and railcars) caused by an overall slowing of the system and from the need to purchase additional equipment to restore the speed of the system where railroad customers could not accept a slowdown. Development of even a rough estimate of the cost attributable to a reduction in the effectiveness of utilization of existing equipment would require information on existing capitalization and amortization schedules. This information is not available. If it is assumed, however, that a general slowing of the system by five percent could result from this operational change and that just the locomotive fleet size was increased by five percent to compensate, the cost would be approximately $1.5 billion for new locomotives. Changes in the speed of the railroad system which were either less than or greater than five percent would be expected to result in proportionally either less or greater costs.

The potential for the loss of all of the emission benefits which were previously estimated for this approach stems from the emission and power characteristics of the locomotives. Locomotive emission rates for HC and NOx, when expressed in terms of mass per unit of time, are approximately halved by changing from throttle notch eight to notch five. The power of the engine is also reduced by approximately one-half as a result of a change between these two notch positions. If the time that a line-haul locomotive spends in an urban region (leaving, entering, or passing through) were to double* as a result of the reduction in power due to operation in notch five versus notch eight, all apparent emission benefits from the change would be lost.

Estimates of the costs of modifying locomotive duty cycles are summarized in Table 27. Lifetime savings are projected for all shut-down scenarios relative to the historical duty cycle. If railroads have already implemented locomotive shut-down at 50°F and above to conserve fuel, these savings ($21,400) can not be counted as part of an emission control scenario. Under this modified duty-cycle condition, some cost ($10,300 to $17,400; i.e., $21,400 savings for 50°F shutdown exceeds the $4000 to $11,100 savings at 32°F) would be associated with shut-down at temperatures just above 32°F and an effect ranging from a small saving ($3,400; i.e., $24,800 minus $21,400) to a cost ($11,200; i.e., $10,200 minus $21,400) could be attributable to shut-down below 32°F.

8.2 Application of Emission Control Technology

Emissions test data on five control technologies were presented in the literature. These data were used in Chapter 7 to develop estimates of the effects of the technologies if applied to locomotive engines. The cost estimates for the application of each of the five control technologies are developed below.

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* Doubling of the time; i.e., halving the speed, that a train spends in traversing a section of track as a result of halving the power setting of the locomotives is possible because the power required to move a train relative to speed is dictated primarily by rolling resistance and grade factors which tend to be linear. If aerodynamic drag predominated in trains, as it does in automobiles, the reduction in speed would be less than 50 percent when the power was reduced by one-half, because aerodynamic drag does not decrease linearly with speed.

Table 27

Summary of Costs: Duty Cycle Modification Relative to Historical Duty Cycles

	Cost per Locomotive ($)			
	First	Maintenance	Fuel	Total
Engine Startability Temperature				
Under 32°F	12,200-24,800	26,500-28,500	(63,500)[1]	(10,200-24,800)
Just above 32°F	6,900-12,000	24,000-26,000	(42,000)	(4,000-11,100)
50°F and above	0	0	(21,400)	(21,400)
Limiting high power usage.[2]	0	0	0	0

1/ Discounted at 10 percent per year over 15 year locomotive life. Values in ( ) indicate savings.

2/ Assumes that no significant slowing of the rail system would occur. If slowing by five percent were to occur, first cost would be approximately equivalent to a five percent increase in the cost of every locomotive in service, i.e., about $50,000 with the potential for no improvement in emissions.

8.2.1 Modification of Injector Design

Changes to the fuel injector can be expected to occur in the number, size and location of the fuel orifices at the tip of the injector and in changes to the sac volume. The design and incremental manufacturing costs for a redesigned injector is estimated to be no more than $5 to $10. For a typical 16 cylinder locomotive the cost would, therefore, be between $80 and $160. Development work leading to the optimum injector design should not be very great and can be expected to cost on the order of $100,000 to $200,000 for each locomotive manufacturer. The development costs for the two manufacturers, when distributed over locomotive production for five years results in a per locomotive cost of between $35 and $70. The total cost per locomotive for the use of redesigned injectors is estimated to be between $115 and $230. Relative to the price of a set of present design injectors ($2,500), the cost increase represents a change of between five and nine percent.

8.2.2 Modification of Injection Timing

The design and manufacturing costs are not expected to be large for the modified hardware necessary for the application of a fuel injection timing schedule which is different from that presently used. This component of the total cost of changing fuel injection timing can safely be estimated as being no more than $100 per locomotive. The cost of development work necessary to define the optimum injection timing can, however, be expected to be significant because of the tradeoffs which will have to be made between each emission specie (HC, CO, NOx, and particulate or smoke) as well as fuel economy. These development costs can be expected, therefore, to be similar to but somewhat lower than those for the development of a cylinder head for use with glow plugs. The cost per locomotive is, therefore, estimated to be between $200 and $300 when the development costs are spread over five years of production. The total cost per locomotive for the application of retarded injection timing is projected to be in the range of $300 to $400. Relative to the $10,000 to $12,000 price of the fuel injection pumps and injectors used on locomotives, these costs represent a change of between two and four percent. The lifetime cost for the 1-2 percent fuel economy penalty is estimated to be between $8,000 and $16,000.

8.2.3 Exhaust Gas Recirculation

Successful application of exhaust gas recirculation (EGR) to locomotive diesel engines will require resolution of problems associated with the design and development of the EGR system as well as problems of engine durability associated with the use of EGR on these engines.

The readily identifiable problems or questions which will require resolution prior to the successful application of EGR to locomotives are: 1) the choice between the use of either cooled or uncooled exhaust gases for recirculation, 2) the degree to which particulate matter is removed from the gases which are to be recirculated, 3) the location for the introduction of the recirculated exhaust gases into the engine intake system, and 4) the methods for either reducing or eliminating the deleterious effects of exhaust gas recirculation on engine durability. These factors are discussed briefly below with the objective of identifying a representative system design.

Data in Reference 3 does not show a substantial difference between the effectivenesses of cooled and uncooled EGR in the control of NOx emissions. On this basis, it appears that the less costly, uncooled EGR method could be selected by locomotive manufacturers. One locomotive manufacturer expressed the opinion, however, that cooled EGR would be required to maximize the benefits of EGR while avoiding thermal problems in the engine which may be associated with uncooled EGR.

Considerations of engine durability and particulate matter removal are interrelated and will be treated here as a single entity. Particulate material contained in the exhaust gases of diesel engines, if recirculated, can cause accelerated wear in the engine, deposit build up in the engine intake system downstream of the point of EGR admission and contamination of the lubricating oil. Reductions in the amount of particulate materials which is recirculated should reduce the deleterious effects of EGR. Two approaches could be considered for reducing the amount of particulate material which is recirculated. These approaches are the application of a cyclone separator where the heavier and/or larger particles are separated from the gas stream or the use of filters which trap the particulate material. The advantage of the cyclone separator approach is that it is self cleaning and requires little maintenance. Its disadvantage lies in its inability to remove the smaller and/or lighter particles. As a consequence, the smaller particles will pass through the separator and would be admitted into the engine. The advantage of the filter approach is its ability to remove much of the fine particulate material. The disadvantage of the filter approach is the rapid plugging of the filters and the subsequent need for the addition of an automatic process for cleaning or regeneration of the filters. Because of the established long term reliability of operation of cyclone separators versus a filtering approach, manufacturers can be expected to view the cyclone separator as the preferred first approach. (Successful development of filters for use on heavy-duty diesel engines applied to road vehicles coupled with transfer of this technology to locomotives could result in the displacement of cyclone separators as the preferred approach.) The use of filters may be viewed as a fall back position if engine durability proved to be unacceptable because of inadequate removal of fine particulate material by a cyclone separator and if the application of other methods of increasing durability proved to be inadequate. Methods for increasing engine durability are expected to include improvements in lubricant filtration and changes in the metallurgy and/or surface finish of such components as cylinder liners, piston rings, camshaft and tappets, bearings and journals and valve stems and valve guides.

Factors bearing heavily on the selection of the point for admission of the EGR into the engine intake system are the effects of deposits on components of the intake system (100 percent particulate removal is not achieved by either particulate removal system) and the requirements for delivering the recirculated gases to the engine intake. If the recirculated exhaust gases were introduced before the turbocharger, deposit build-up would be expected to occur throughout the engine intake system including the compressor section of the turbocharger, the intercooler, and the intake air preheater (if used as a starting aid). The accumulated deposits would degrade the performance of these components. The volumetric capacity of the turbocharger would also have to be increased to compensate for the temperature increase and consequently volumetric increase of the gas (air plus exhaust) being supplied by the turbocharger. Because of the small positive pressure differential which exists between the gas in the exhaust manifold and the entry of the turbocharger compressor section, pumping of the exhaust gases into the intake manifold could probably be avoided. If the recirculated exhaust gases were introduced downstream of the compressor, intercooler and air preheater, the performance of these components would not be degraded. Pumping of the recirculated gases into the intake manifold would, however, be necessary because of the high pressure in the intake manifold. Manufacturers could reasonably be expected to introduce the recirculated exhaust gases downstream of the compressor, intercooler and air preheater because this location would avoid degredation of the performance of those components.

The configuration of an EGR system for a locomotive engine can, therefore, be expected to be as follows; a compressor to raise the pressure of the gas being recirculated, a turbine for driving the compressor, a cyclone separator, a flow control valve, a flow control valve actuator and its control system, and plumbing between the system components. The compressor and turbine for pumping the exhaust gases into the intake manifold would be similar to a turbocharger and can, as a first estimate, be expected to cost between 15 and 20 percent of that of the locomotive engine turbocharger. With a price range of between $25,000 and $30,000 for a turbocharger, these percentages correspond to a cost of between $3,000 and $6,000. The per locomotive cost of the components of the EGR system, including redesigned exhaust and intake manifolds is expected to be in the $8,000 to $15,000 range. The incremental cost of the improved lubricant filtration system and modified (design and metallurgy) cylinder lines, rings, bearings, and valve train is estimated to be between $1,000 and $1,500 per locomotive. The costs for the development of a marketable EGR system and the associated engine modifications would be higher than those for a cylinder head modification but lower than those for a major redesign to accommodate the use of antifreeze. The cost is, therefore, estimated to be on the order of $5,000,000 to $10,000,000 for the two manufacturers. When spread over a five year production period, these costs would represent a per locomotive cost of between $850 and $1,700. Increases in the cost of maintenance should not be large and would be attributable primarily to increases in the cost of lubricant filtration. A reasonable cost for this maintenance would be between $500 and $1,000 spread over the lifetime of the locomotive. The lifetime cost for the 1 percent fuel economy penalty is estimated to be $8000. The total projected cost per locomotive associated with exhaust gas recirculation is, therefore, between $21,350 and $33,200.

8.2.4 Reduced Scavenging (Increased Internal Exhaust Gas Recirculation)

The purpose of the emission control approach addressed in this sub-section is the dilution within the engine cylinders of the fresh air charge for each power stroke with some of the exhaust gases from the previous power stroke. Dilution of the intake air with exhaust gases is achieved by the retention of some of the exhaust gases in the cylinder. In the EMD 2-stroke engines, removal of the exhaust gases from the cylinder can be viewed as a two step procedure. The first step is the opening of the exhaust valves which allows venting of the relatively high pressure gases through the valves. The second step is the opening of the intake ports which allow the pressurized intake air to enter the cylinder and blow the remaining exhaust gases out of the cylinder through the open exhaust valves. This second step is referred to as scavenging. Reducing the amount of scavenging which occurs could be accomplished by three methods; i.e., either by earlier closing of the exhaust valves, by reducing the pressure of the intake air or by a combination of the two previously identified methods. In 4-stroke engines which are used by GE, removal of the exhaust gases can be viewed as a three stage procedure. The stages are the opening of the exhaust valves which allows venting of the relatively high pressure gases, displacement of gases in the cylinder through the exhaust valves by the piston as it rises in the cylinder and some scavenging of the combustion chamber by pressurized intake air during the short period that both the intake and exhaust valves are partially open. The period while both the intake and exhaust valves are partially open is referred to as the valve overlap period. On a 4-stroke engine which is turbocharged (intake air is pressurized) the amount of exhaust gas which is retained can be increased by either reducing the pressure of the intake air or by reducing the valve overlap. In a nonturbocharged engine which operates at the low speeds typical of locomotive engines, an increase in valve overlap achieved by earlier opening of the intake valve would be one method of increasing the quantity of exhaust gases which are retained.

In the experimental work on reduced scavenging reported in the literature, the desired objective was achieved by bleeding intake air out of the intake manifold. While this approach is suitable for use in an experimental program, it is not judged to be appropriate for use on production locomotives. On production locomotives, increasing the amount of exhaust gas which is retained would probably be achieved through changes in the timing of the valves or through changes in the air delivery characteristics of the turbocharger.

Both of these approaches would require development work to define the changes required and some small increase in the manufacturing cost of the redesigned parts to cover changes in production tooling. Development costs per manufacturers of $250,000 to $500,000 should be sufficient for these changes. This cost would translate into a per locomotive cost of between $80 and $170. Adding a cost of between $40 and $50 per locomotive to cover manufacturing costs results in a total cost estimate of between $120 and $220 per locomotive. Maintenance costs should not be affected by this approach to the control of exhaust emissions. The lifetime cost for the 1 percent fuel economy penalty is estimated to be $8000.

8.2.5 Water Injection

Two procedures can be considered as offering potential for introducing water into the combustion chambers of a locomotive engine. The procedures are: 1) the spraying of the water into the intake system of the engine, and 2) the formation of a water/fuel emulsion which is injected into the combustion chambers by the fuel injection system. Some basic considerations pertaining to the use of water injection are discussed below prior to the development of an estimate of the cost of water injection for a locomotive engine.

Fundamental to either method for the introduction of water, is the need to provide a tank on the locomotive for storage of the water. References 3 and 4 showed that the water injection rate should be about 75 percent of the fuel injection rate. With this water injection rate, a water storage tank volume of about 2,250 gallons would be required to correspond to the 3,000 gallon fuel tank which is most commonly used. Locomotive fuel tanks occupy essentially all of the space between the trucks (wheel, motor assemblies) of the locomotive and extend the full width of the locomotive. Dimensionally, the fuel tanks are about 9 feet wide, 3 feet deep and 16 feet long. The dimensions for a water tank which would hold the required volume of water would be about 9 feet by 3 feet by 12 feet. Presently, there does not appear to be even a small portion of this space requirement available on locomotives. Reducing fuel volume is not considered to be a viable option for securing space for water storage because the present volume of fuel will support full power operation for no more than about 16 to 20 hours and railroads are already expressing a desire for additional fuel volume. Increasing the size of the locomotive to accommodate the water tank also does not appear to be a viable alternative. Width and height increases are not possible because of clearance requirements between locomotives on parallel tracks and in tunnels. Any increase in the length of a locomotive would be limited to the difference between the present length of the locomotive and the maximum length as defined by the minimum radius of the turns in the track on which the locomotive must operate. Locomotive manufacturers indicate that locomotives are already as long as is possible within the constraints of the tracks on which they will be operated. At this time, the addition of a tender to each locomotive appears to be the only option whereby the necessary water tank volume could be provided.

Two other factors which would impact the use of water injection on locomotive engines are the weight increase of the locomotive and the availability of water of appropriate purity. Locomotive axle loading is limited to 70,000 pounds because of the load carrying limitations of the track. Loads imposed on the track by each axle of a fully fueled and operational locomotive are presently on the order of 65,000 pounds or higher. There is, therefore, very little load carrying reserve capacity available. If the use of a tender were adopted, the weight constraints would be eliminated because the weight of the tender would be supported by a separate set of wheels.

The other factor which has been identified by locomotive manufacturers as a source of concern with respect to the use of water injection is the availability of pure water. Use of water which contains dissolved minerals, so called hard water, in the water injection system would result in the formation of deposits in the water delivery system, the combustion chambers, the exhaust system and on the turbocharger of the locomotive engine. Deposit formation on the system components must be avoided because of resulting degradation in the performance of the locomotive and of the water injection system. The formation of deposits can be controlled by the use of contaminant free water. The cost of facilities to produce water of the necessary purity plus the distribution and storage of the water at each refueling point are estimated to be equivalent to about a one percent increase in the cost of fuel, i.e., approximately $8,000 during the lifetime of a locomotive.

If it is assumed that a water tender would be employed with each locomotive, the cost of the water injection system would consist of the tender, the water delivery and metering system and a system to prevent freezing of the water. The cost of the tender is estimated to be between $20,000 and $40,000 and would include a diesel fueled heater system to prevent freezing of the water. Introduction of the water into the combustion chambers may be achievable by either of the following methods. The first method for water delivery would be through the formation of a fuel-water emulsion which would be injected into the cylinders by a suitably modified fuel injection system. The hardware components of this system would be pumps and flow control valves for the delivery of the fuel and water to the emulsifier, the emulsifier, modified fuel injection pumps and injectors, a modified fuel return line which carried unused fuel and water back to the emulsifier and a fuel tank heater to control fuel waxing (waxing is presently controlled by the return of warmed fuel to the fuel tank). The cost for this approach can be expected to be between $10,000 and $15,000 per locomotive including development costs.

The second method for accomplishing water injection would be through the introduction of the water into the intake air stream. On the 4-stroke engines produced by GE this could be accomplished by the continuous introduction of water immediately upstream of the intake valves. Including development costs, the cost of the continuous flow system is estimated to be between $3,000 and $5,000 per locomotive. On the 2-stroke engines produced by GM, timed water injection would appear to be necessary so as to avoid puddling of the water in the intake manifold. For the timed system, the cost is estimated to be about $2,000 higher or between $5,000 and $7,000 per locomotive.

Because the cost of introducing water into the intake air is expected to be lower than the cost of the water-fuel emulsion system, it would appear that it could be the preferred system. There are, however, presently unanswered questions pertaining to the successful control of corrosion in the engine associated with the introduction of the water into the intake air which may make this system impractical. The estimated total cost per locomotive of a water injection system could be between a low of $23,000 where the water is injected into the air entering the engine and a high of $55,000 with an emulsion system plus an annual cost for water of about $1,000. Lifetime costs are projected to be between $31,000 and $63,000. Because of problems inherent to the use of water injection as an emission control concept for locomotives (addition of a tender, freeze protection, providing and distributing water of adequate purity and corrosion control) it must be viewed as an approach with little practical potential.

For ease of reference, the estimates of the costs of the five emission control technologies are summarized in Table 28.

8.3 Cost-Effectiveness

The financial efficiency of an emission control strategy can be measured by developing the ratio of the costs incurred to the benefits realized. This ratio is referred to as the cost-effectiveness of the control strategy and is usually expressed in terms of lifetime costs and lifetime benefits for the equipment involved.

The effects on emission rates and on fuel consumption of the control strategies which were analyzed previously are summarized in Table 29. These values are based on historical locomotive duty cycles. Since there are no data upon which to base an estimate of the extent to which railroads have taken advantage of the shutdown capability of recent design locomotives, i.e., implemented locomotive shut-down at 50°F and above as a fuel conservation measure, no attempt was made to estimate benefits under revised duty cycles. Lifetime changes in the mass of emissions contributed by an average locomotive within AQCRs and the change in fuel consumed by an average locomotive over the 15 year locomotive lifetime are shown in Table 30. For each control strategy and pollutant, the values shown represent the change relative to historical duty cycles.

The costs which have previously been developed are summarized in Table 31. Fuel and maintenance costs are discounted to the year that an appropriately modified locomotive is placed in service. Combining the costs and emission benefits results in the cost-effectiveness values for each control procedure as shown in Table 32. In the case of the engine shutdown options, total costs (savings) are equally divided between HC, CO, and NOx in determining the cost-effectiveness values. In the cases where emission control hardware is employed, costs are equally divided between the

Table 28

Summary of Costs:
Application of Emission Control Technology

	Cost Per Locomotive ($)			
Technology	First	Operating & Maintenance	Fuel[1]	Total
Modified Injectors	115-230	0	0	115-230
Modified Injection Timing	300-400	0	8,000-16,000	8,300-16,400
Exhaust Gas Recirculation	12,850-24,200	500-1,000	8,000	21,350-33,200
Reduced Scavenging	120-220	0	8,000	8,120-8,220
Water Injection	23,000-55,000	8,000[2]	0	31,000-63,000

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[1] Lifetime cost discounted at annual rate of 10 percent.

[2] Approximately one percent of the lifetime cost of fuel consumed discounted at 10 percent per year.

Table 9

Percent Change in Lifetime Emissions and Fuel Consumption By Control Procedure Relative to Historical Duty Cycles

	Emissions (% change)				Fuel Consumption
Control Procedure	HC	CO	NOx	Smoke	(% Change)
Engine Shut-down					
° below 32°F	-17	-13	- 7	N.A.[1]	- 8
° at 33°F and above	-10	- 8	- 4	N.A.	- 5
° at 50°F and above	- 5	- 4	- 2	N.A.	- 3
Eliminating high power settings		[2]			
Injection Timing Retard	0	+20	-25	+50	+1 to +2
Modified Injectors	-20	-20	+25	0	0
EGR	-20	+200	-45	+200 to +700	+1
Reduced Scavenging	0	+200	-10	+200	+1
Water Injection	+10	-5	-15	0	0

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[1] N.A. - effect could not be estimated from the data (expected to be very small).

[2] Significant uncertainties with the practicality of this system makes its use questionable. Values were, therefore, not presented.

Table 30

Lifetime Change in Mass of Emissions in AQCRs and Fuel Consumed For an Average Locomotive Relative to Historical Duty Cycles[1]

Control Procedure	HC (tons)	CO (tons)	NOx (tons)	Fuel (1,000 gal)
Engine Shut-Down				
°below 32°F	-6.4	-9.2	-26.0	-120.0
°at 33°F and above	-3.8	-5.7	-14.9	-75.0
°at 50°F and above	-1.9	-2.8	-7.4	-45.0
Injection Timing Retard	0	+14.2	-93.0	+30.0
Modified Injectors	-7.5	-14.2	+93.0	0
EGR	-7.5	+71.1	-167.3	+15.0
Reduced Scavenging	0	+71.1	-37.2	+15.0
Water Injection	+3.8	-3.6	-55.8	0

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[1] Derived from emission rates and fuel consumption values in Chapter 5. An average locomotive is defined as 20% of a switch and transfer locomotive and 80% of a line-haul locomotive (derived from the 3.93:1 ratio for line-haul to switch and transfer locomotives.)

Table 31

Lifetime Costs for Emission Control Procedures per Locomotive Relative to Historical Duty Cycles

Control Procedure	Purchase Price ($1000)	Maintenance[1] ($1000)	Fuel[1] ($1000)	Total ($1000)
Engine Shutdown ° 32°F and below	12.2 to 24.8	26.5 to 28.5	-63.5	-24.8 to -10.2
° at 33°F and above	6.9 to 12.0	24.0 to 26.0	-42.0	-11.1 to -4.0
° at 50°F and above	0	0	-21.4	-21.4
Injection Timing Retard	0.3 to 0.4	0	8.0 to 16.0	8.3 to 16.4
Modified Injectors	0.1 to 0.2	0	0	0.1 to 0.2
EGR	12.9 to 24.2	0.5 to 1.0	8.0	21.4 to 33.2
Reduced Scavenging	0.1 to 0.2	0	8.0	8.1 to 8.2
Water Injection	23.0 to 55.0	8.0	0	31.0 to 63.0

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[1] Values given for maintenance and fuel costs are discounted costs to the year that the modified locomotive is produced. The discount rate used is 10 percent per year. Fuel cost of $1 per gallon is assumed. Values preceeded by a negative sign are savings.

Table 32

Cost Effectiveness of Control Strategies Based on Historical Duty Cycles[1]

Control Procedure	Cost Effectiveness ($/ton) HC	CO	NOx
Engine Shut-Down			
°below 32°F	(1,290) to (755)	(900) to (530)	(320) to (185)
°at 33°F and above	(975) to (700)	(650) to (480)	(250) to (180)
°at 50°F and above	(3,755)	(2,550)	(965)
Injection Timing Retard	---	---	85 to 175[2]
Modified Injectors	8 to 15[3]	4 to 8[3]	---
EGR	1,425 to 1,765[4]	---	65 to 95[4]
Reduced Scavenging	---	---	220[5]
Water Injection	---	4,305 to 8,750[6]	280 to 565[6]

1/ Numbers in ( ) indicate savings rather than costs. Costs are equally divided between the pollutants which are reduced by the control procedure.

2/ Injection timing retard reduced NOx while increasing smoke and CO and with minimal impact on HC.

3/ Modified injectors reduced HC and CO, increased NOx without affecting either CO or smoke.

4/ EGR reduced HC and NOx, increased CO and smoke.

5/ Reduced scavenging reduced NOx, increased smoke and CO without affecting HC.

6/ Water injection reduced CO and NOx, increased HC and did not affect smoke.

pollutants which would be reduced through the application of the control technology. Another method of calculating the cost-effectiveness would be to assign the total cost of the emission control technology to the pollutant which the technology is primarily designed to control. For example, EGR would be applied for the control of NOx and the HC benefit could be treated as being free rather than distributing the costs equally between HC and NOx as was done in Table 32. If this were done, the cost-effectiveness value for HC would be zero and the value for NOx would be doubled to between $130/ton and $190/ton. It should be noted that the application of a technology which reduces one pollutant may result in an increase in one or more of the other pollutants, e.g., NOx and HC emissions were reduced by EGR, but smoke and CO emissions were increased (see Table 29). (Note that none of the technologies for which data were available showed any benefits with respect to the control of smoke (particulate) emissions (Table 29)). The true costs and, therefore, the cost-effectivenesses of technologies which produce adverse effects would have to be increased to cover the application of additional technologies which would neutralize some or all of the penalties. For example, the cost-effectiveness of control of HC emissions through the use of modified injectors is 8 to 15 dollars per ton (Table 32) but with an accompanying increase in NOx emissions. If it were to be assumed that an increase in NOx emissions could not be accepted but that an increase in smoke emissions could be accepted, then combining injection timing retard and modified injectors (Table 29 shows a canceling of the effects of these technologies on NOx emissions) could result in an acceptable procedure. The cost-effectiveness value for the control of HC emissions would then be between $885/ton and $2215/ton (cost of both technologies (Table 31) divided by HC benefits from modified injectors (Table 30)).

Examples of the cost-effectiveness of controlling HC, CO, and NOx emissions from other sources are shown in Table 33 for purposes of comparison. Comparing the cost-effectiveness values for locomotives, by control procedure, with those for other sources shows that the cost-effectiveness of control for locomotives is not excessive. Combining emission control technology procedures to limit or change the area of a negative effect, as was done in the example above, may result in substantial change in the cost-effectiveness values. Combinations of emission control technology and engine shutdown capability could, however, result in the reduction in emissions at a net savings because of the reductions in fuel consumption.

It is appropriate to note at this point that there were no data on emission control technologies for the control of smoke emissions and that cost and cost-effectiveness estimates for

Table 33

Cost Effectiveness for Controlling Non-Locomotive Sources

	Cost Effectiveness ($/ton)		
Control Strategy	HC	CO	NOx
LDV, statutory standard	508[1]	44[1]	
LDV, I/M	943[1]	57[1]	
LDT, statutory standard	207[1]	14[1]	
Industrial Boilers - Coal Fired			130 to 1500[2]
Industrial Boilers - Gas & Residual Oil Fired			500 to 1400[2]
Coke-ovens (80% HC reduction)	490[2]		
HDGE, evap. control (evap, 5.8 to 0.5)	112[1]		
Motorcycle standards	616[1]		

1/ "Revised Gaseous Emission Regulations for 1985 and Later Model Year Heavy-Duty Engines," U.S. EPA, OMS, ECTD, July 1983.

2/ Federal Register, June 19, 1984, 49 FR 25144 and 49 FR 25145.

the control of smoke emissions are not included. Incorporation of a technology which would either negate the smoke emission penalties caused by other technologies or which would reduce smoke emissions could result in a change in the cost-effectiveness values which are shown.

9.0 EXISTING STATE AND LOCAL REGULATIONS

This portion of the report addresses "the status and effect of current and proposed state and local regulations affecting such emissions," i.e., Section 404(a)(3).

To fulfill the requirements, the study evaluated the status and effects of the subject regulations in the following manner. First, the relevant regulations were compiled from political jurisdictions (subdivisions) across the nation. Second, the regulations were evaluated to determine their effects on: 1) health and welfare, 2) application of operational and technical controls to railroad emissions sources, and 3) interstate commerce.

A review of the literature showed that although at least one study (Sturm, 1973) had documented a number of typical state and local regulations, there was no existing compilation or evaluation of the effects of the standards which would be useful to this study.

The majority of information used in this analysis was obtained from a survey of the 50 states and 229 local (i.e., regional, county, and city) air pollution control agencies. The address of each office was obtained from the Directory of Governmental Air Pollution Control Agencies (APCA, 1975). The questionnaire requested three types of information: 1) all current and proposed regulations which pertain to or could be construed to pertain to locomotives, 2) any problems with enforcement which they may have encountered, and 3) opinions as to whether there was a need for Federal regulations.

State laws which incorporated specific language as to the level of control were obtained directly from the statutes. The remaining information came from the diesel-electric locomotive manufacturers, the Association of American Railroads, railroad companies, and the Department of Transportation.

9.1 Survey of Existing Regulations

9.1.1 Survey Returns

Of the 279 governmental air pollution control agencies surveyed, a total of 308 separate replies were received. The additional responses are accounted for by the fact that some questionnaires were sent to regional authorities which had several city or county members within the region. In these cases, the region's response was tabulated for each individual subdivision. Responses were received from 92 percent of the 279 requests, as tabulated in Table 34.

Table 34

Survey Returns

Control Authority	Total Requests	Total Responses	Percent Return	Jurisdictions Represented
State	50	47	90	47
Local	229	207	94	261
Total	279	254	92	308

The compilation of emission regulations by this study should be viewed as being a reasonable documentation of the existing approaches and not a complete bibliography in itself. It represents a best effort at cataloging responses which were, at times, incomplete and fragmentary. All of the submitted material was reviewed and, in some cases, regulations which could be construed to include railroad rolling stock were identified in addition to those pointed out by the respondents. If an incomplete text of the regulations was included, it is possible that some standards were mistakenly included or excluded because of a lack of other relevant details. Also, as a compromise in the length of this analysis, the regulations were condensed and this may have unavoidably added some ambiguity.

9.1.2 Types of Regulations

Two types of state and local regulations were found which pertained to railroad rolling stock: gaseous and particulate. The vast majority of the regulations pertained to particulate emissions. The gaseous emissions were defined in terms of specific chemical pollutants (HC, CO, NOx, and SO_2) and odor. None of these regulations specifically cited permissible emissions rates, but instead made it illegal for the emissions to create a nuisance. The nuisance regulations that pertained to excessive odor were not cataloged.

The particulate regulations almost exclusively pertain to visible smoke emissions, with only a very small number citing specific emission rates.

Visible smoke standards define allowable emissions in terms of an acceptable percent opacity or Ringelmann number. In many cases, the standard is expressed by both measurements. The percent opacity is defined as that fraction of light transmitted from a source which is prevented from reaching the observer or instrument receiver. The Ringelmann scale was developed by the U.S. Bureau of Mines as a measurement for black and white smoke. As originally developed, Ringelmann #1 was to equal 20 percent opacity, Ringelmann #2 equals 40 percent, #3 equals 60 percent, #4 equals 80 percent, and #5 equals 100 percent.

9.1.3 Typical Regulation

Regulations imposed by the State of Illinois are presented as an example of typical regulations. The regulation provides that:

"Rule 707. Diesel Engine Emission Standards.

707(a) The visible emission standard in Rule 706 shall not apply to diesel engines.

707(b) With the exception of Rule 707(e) diesel engines manufactured before January 1, 1970, shall not be operated in such a manner as to emit smoke which is equal to or greater than 30 percent opacity except for individual puffs of smoke. Individual puffs of smoke shall not exceed 15 seconds in duration.

707(c)(1) Diesel engines shall be operated only on the specific fuels as specified in the engine manufacturer's specifications for that specific engine, or on fuels exceeding engine manufacturer's specifications.

707(c)(2) Persons liable for operating diesel engined fleets wholly within S.M.S.A. shall furnish to the Technical Secretary of the Illinois Air Pollution Control Board once each year, proof that the fuel purchased and used in their operations conforms to Rule 707(c)(1).

707(d) All diesel engines operated on public highways in Illinois coming from out of the State shall conform to Rule 707(b).

707(e)(1) No person shall cause or allow the emission of smoke from any diesel locomotive in the State of Illinois to exceed 30 percent (30 percent) opacity.

707(e)(2) Rule 707(e)(1) shall not apply to:

(A) Smoke resulting from starting a cold locomotive, for a period of time not to exceed 30 minutes.

(B) Smoke emitted while accelerating under load from a throttle setting other than idle to a higher throttle setting; for a period of time not to exceed 40 seconds.

(C) Smoke emitted upon locomotive loading following idle; for a period of time not to exceed 2 minutes.

(D) Smoke emitted during locomotive testing, maintenance, adjustment, rebuilding, repairing or breaking in; for an aggregate of 10 minutes in any 60-minute period.

(E) Smoke emitted by a locomotive which because of its age or design makes replacement or retrofit parts necessary to achieve smoke reduction unavailable. These locomotives shall be retired at the earliest possible time."

In states where there are marked differences in altitude, there are sometimes different standards depending upon altitude, e.g., below and above 5,000 feet.

9.1.4 Compilation of State and Local Standards

The stated applicability of the regulations varied from very specific to very broad. In general, the regulations were expressed in terms of steady-state emissions with specific exceptions (Table 35). The following definitions were used in compiling and categorizing the state and local regulations:

1. Stated applicability of the regulation to:

a. Locomotives: Usually specific to railroad industry diesel-electric locomotives, but may include steam-powered locomotives and amusement park operations as well.

b. Generic Description: Includes all sources within a general description class, e.g., internal combustion engine, diesel engine, motor vehicle, mobile source. This category may include locomotives, locomotive diesel engines, refrigerator cars, and other railroad rolling stock.

c. Emissions into the Atmosphere: This category contains the most inclusive of the regulations that specifically cite allowable emission levels. A phrase such as "maximum allowable discharge into the atmosphere from any source" is typical of the regulatory language. When a regulation was written to include a large variety of sources and only incidentally mentioned railroads, the regulation was placed into this category.

d. Nuisance: An all-inclusive category for any emission which "causes or contributes to the condition of pollution." Because of its vagueness, this type of regulation is seldom enforced.

2. Exceptions

a. Excursions: This is a general category which limits temporarily excesses of the continuous standard in duration and intensity.

b. Maintenance: These exceptions apply when the source is being repaired, adjusted, or rebuilt.

c. After Idle: Higher allowable emission levels following a prolonged period of idle may be necessary due to below normal operating temperatures or carbon loading.

Table 35

Categorization of State and Local Regulations

	Applicability of Regulations					Exceptions to the Rules					Subjective Evaluation			
											Enforcement Problems		Need for Federal Regulation	
	No Regulations	Locomotive	Generic Description	Emissions Into Atmosphere	Nuisance	Excursions	Maintenance	After Idle	Cold Start	Other	Yes	No	Yes	No
State Level	34% (16)	21%(10)	30%(14)	34%(16)	4%(2)	57%(2)	19%(9)	17%(8)	19%(9)	11%(5)	8%(2)	92%(23)	74%(26)	26%(9)
Local Level	39% (101)	10%(27)	18%(48)	28%(73)	13%(35)	42%(110)	4%(10)	5%(12)	8%(20)	4%(10)	15%(19)	85%(105)	84%(114)	16%(22)

d. Cold-Start Smoke: Refers to the blue-white smoke resulting from cold combustion chambers.

e. Other: This category contains exceptions which are not covered by the other classifications.

From the list of definitions it should be clear that emission standards for categories other than "Locomotive" are included if: 1) they may be construed to include locomotives, or 2) they may limit emissions from secondary rolling stock. For example, when the generic classification referred to diesel-powered vehicles or motor vehicles, the standard for emissions into the atmosphere was included to account for secondary rolling stock.

Survey answers with regard to current enforcement problems and the need for Federal preemptive standards are cataloged under the headings entitled "Enforcement Problems" and "Federal Regulations," respectively (Table 35).

9.1.5 General Results

The results of the survey are summarized in Table 35. The percentages are based on the total number of responses to each of the three questions. The number of cases upon which the percentage was calculated is included to qualify the figure. The percentiles listed under the "Applicability of Regulations" and "Exceptions to the Rules" categories do not total 100 since some political jurisdictions have more than one relevant standard.

The basic state laws are clean air acts, enacted in response to the Federal Clean Air Act of 1967. Almost all states have sections in their laws which either directly mention locomotives or could be construed to include locomotives and secondary railroad rolling stock. Three states have a Ringelmann or opacity standard in the law: Maine, Kentucky, and California. Most states, however, authorize the state air pollution control agency to develop suitable standards.

Of the state air pollution control authorities that responded, 66 percent or 31 had a steady-state standard which applied to railroad rolling stock. No states had a nuisance standard only.

For local air pollution control authorities, 60 percent or 156 had a suitable steady-state standard. Eight percent or 21 had a nuisance standard only; therefore, 52 percent or 135 localities had what might be termed a readily enforceable regulation.

There is no interstate or intrastate consensus as to the most appropriate level of control among the air pollution authorities that do have regulations. Minnesota controls locomotives to 10 percent opacity, while Iowa controls them to 40 percent. California's standard is R#2 or 40 percent opacity, but in San Francisco it is R#1 or 20 percent opacity. The exceptions to the regulations are also inconsistent.

There is no consistency with regard to the authorized regulatory agency. Some states, Maryland and Texas for example, preempt local control, although localities can and do adopt and enforce the state regulations. Some states (e.g., Michigan, Kansas and Ohio), have no state regulations, but individual localities do. In most states, there are both state and local regulations.

Several of the respondents exhibited confusion with regard to the authority for regulating this source. Some county air pollution control agencies in California claimed that the state had preempted local railroad regulations, while others had regulations which they were enforcing. (There was also some confusion as to whether locomotives were mobile or stationary sources.) A county in Maryland indicated they thought the Clean Air Act had already preempted other standards and assigned regulatory authority to the Department of Transportation or EPA.

Preemption was not the only reason why some air pollution control agencies did not have regulations. These reasons are listed below:

1. Railroad operations do not draw citizen complaints or the number of complaints is inadequate to justify regulatory action;

2. Only stationary sources are controlled;

3. The appropriate state enabling legislation does not exist; and

4. There are no railroads (Hawaii).

Minnesota has the only regulation that apparently excludes a portion of the railroad rolling stock. All 2-cycle engines are specifically exempted from meeting the regulatory requirements. The majority of diesel-electric locomotives and perhaps all of the diesel-powered secondary rolling stock are, however, 2-cycle engines.

9.1.6 Subjective Questions on Enforcement

Of the respondents that had applicable regulations, there were varying degrees of enforcement ranging from essentially no enforcement to strict enforcement. The reasons given for low levels of enforcement were:

1. No citizen complaints;

2. Other sources are more important;

3. A general lack of time and money, although a definite need for control may have existed; and

4. Enforcement only on citizen complaints, but no real active program.

There was no correlation between the specificity of the regulation (i.e., a locomotive standard being the most specific), and the degree to which it was enforced, excluding those classified as nuisance. California and its localities actively enforce their "emission into the atmosphere" standard against railroad rolling stock.

It was extremely difficult to draw any conclusion from the survey with respect to enforcement problems. Many states and localities indicate they did not consider railroads to be a major problem, did not try to enforce any regulations they might have, and obviously did not think enforcement was a problem. Other localities did enforce their regulations, but found a great deal of cooperation from the railroads, and also did not consider enforcement a problem. The standard enforcement procedure was for the agency to send a letter to the railroad stating that Unit XXX was seen (means visible smoke) at a certain time in a certain place in violation of the regulations, and requested that the railroad rectify the problem. The railroad, in a return letter, would report the steps it had taken to end the emissions. Invariably, the problem, as reported by the railroads, was a malfunctioning part. Most agencies did not have a way to confirm the railroad's report and accepted the report at face value.

Eight percent or two of the 25 states definitely had trouble enforcing their regulations: Maine and Oregon. Fifteen percent or 19 out of 124 localities experienced difficulties. These results must be viewed with some reservations, however, since all of the respondents did not address the question and railroad emissions were not generally viewed as being a problem. Therefore, the only definite conclusion that can be drawn is that at least 15 percent of the localities responding experienced enforcement problems.

Those who reported enforcement problems listed three main types with two concerning the mobility of the locomotives. The first problem is that it is difficult and/or dangerous to follow the locomotives for long enough periods of time to observe violations. This is particularly true where the train runs at relatively high speeds through a countryside where the highway does not parallel the tracks long enough for a car with a smoke observer to follow it.

The second problem is the tendency of the railroads to move their old, less well maintained engines from areas of strict standards and enforcement to areas of loose enforcement. Comments to this effect came from both areas which were receiving the older engines, and those which enforced strict standards and knew that the engines were being sent somewhere else. While many areas had solved their own air pollution problems, they knew it was a short-term solution achieved at the expense of someone else.

The last type of problem cited was a lack of cooperation from the railroads.

9.1.7 Subjective Questions on the Need for Federal Regulations

Of the 35 state agencies responding, 74 percent supported Federal regulation. Of the 136 local agencies, 84 percent felt preemption was desirable. However, these results are qualified by the fact that about 20 percent of the state and local agencies answering "yes," wanted a Federal standard only if the EPA found it necessary. The responses did not distinguish between Federal regulation of new locomotives and Federal regulation of in-use locomotives.

Four percent and 17 percent of the state and local agencies, respectively preferred to retain local enforcement power under Federal standards for more effective and efficient control.

Those that favored a preemptive standard did so mainly because of the interstate nature of railroad operations, stressing the difficulty of enforcing a regulation on a vehicle which may only be within one's jurisdiction on a temporary or occasional basis. Federal regulations could remove this difficulty as well as preventing the transferral of locomotives from jurisdiction to jurisdiction which some railroads now practice.

Commenters also suggested that a preemptive standard would resolve questions concerning the legality of state and local regulations. Four responses included information which explains this jurisdictional problem.

1. A railroad company suggested that local standards do not apply to their operations since they are engaged in interstate commerce, and only the Federal government has regulatory authority;

2. The court upheld the local regulation if the train originated and terminated within local jurisdictional boundaries, but not if it was interjurisdictional in nature;

3. The court upheld local authority to regulate railroads for visible smoke regardless of the train's origin; and

4. Legal precedent exists for locally regulating a source engaged in interstate commerce based on the U.S. Supreme Court case of Huron Portland Cement Company v. City of Detroit, 362 U.S. 440 (1960), in which the enforcement of a local smoke standard against a vessel was contested.

Those who favored local or state standards generally had effective enforcement, and saw no need for Federal intervention. They also pointed to local problems, such as large switchyards, which they thought could be better controlled by local government.

9.2 Effects of Existing Regulations

9.2.1 Health and Welfare

This evaluation focuses on visible emissions (smoke) from railroad sources because existing state and local regulations do not focus effectively on gaseous emissions.

The direct impact on human health of existing state and local regulations is impossible to assess at this time because of lack of data on the effectiveness of state and local regulations and because of uncertainties pertaining to the linkage between smoke emissions and human health and welfare. The railroad industry practice of selectively avoiding violations for excessive visible emissions by transferring "dirty" locomotives into areas where it is reasonably certain no punitive action will be taken is understandable, but undesirable. This practice of concentrating high-emitting rolling stock in specific areas may result in concentrated areas of emissions, but insufficient data exist to assess the effect on health and welfare of those areas.

9.2.2 Operational and Technical Controls

Although many factors affect visible emissions from railroad rolling stock, including the quality of fuel and operational practices, the two basic determinants which control smoke are engine design and maintenance.

Diesel engines have inherent design features which prevent a smoke free exhaust under all operating modes. However, by optimizing the combustion chamber geometry and the fuel and air delivery systems, smoke can be reduced. All of the currently manufactured locomotive engines have incorporated modifications to control much of the smoke which still plagues many of the older engines. For this reason, excessive visible emissions from well-maintained engines are, to a large degree, associated with older locomotive units. The problem persists either because low-smoke replacement parts are unavailable or, if these parts are manufactured, they have not been installed because of economic considerations.

Inadequate maintenance is by far the greatest contributor to excessive visible exhaust emissions from this source. Poor maintenance practices are a nationwide problem which persists because the railroads find it economically attractive to defer maintenance. It is, however, not limited to financially distressed companies. The problem is widespread since it affects engines regardless of their age or design sophistication. It is characterized by maladjustment (e.g., fuel injection timing) and malfunctioning hardware (e.g., bad fuel injectors or dirty air filters).

There are exceptions, however, even for well-maintained units. Locomotives, in general, have visible emissions during or following a period of idle because the combustion chamber wall temperatures decrease to the point that the flame is quenched as it nears the walls. When this happens, the fuel in this region is not burned and these liquid hydrocarbons escape through the exhaust system appearing as a white smoke. The other problem, associated with line-haul locomotives, is termed "turbocharger lag." When more power is demanded from the engine, more fuel is added to the combustion chamber. This in turn requires a greater amount of air for complete combustion. However, the turbocharger, which relies on exhaust gas energy to power it, will not gain the additional speed to supply more air until the exhaust energy increases. Because of this period when the turbocharger is not "up to speed" a temporary rich mixture exists in the combustion chamber and results in black smoke, i.e., incomplete combustion. This problem has been alleviated to some degree by locomotive manufacturers.

Switch engines are potentially the most offensive. These units are typically of an older design and may have been removed from other service because of poor reliability. They often receive no preventative type of maintenance and may be repaired only after the higher priority line-haul locomotives.

Switch engines undergo many throttle excursions during their active service. They also idle for long periods of time while awaiting assignment. The high activity levels of these engines plus the fact that they operate in localized areas may predispose them to a high frequency of observation making them a greater source of nuisance. The units, however, do not operate strictly in switchyards, but are used in local service train for distances often exceeding 25 miles from their home base. These locomotives share common problems with line-haul units although in nonnaturally-aspirated switch engines, turbocharger lag is avoided by using a mechanically driven roots blower. The use of this blower, however, makes a switch engine more susceptible to excessive visible emissions at higher altitudes where the air is less dense.

Considerable uncertainty exists in trying to estimate future trends which might affect excessive particulate emissions from railroad rolling stock. The cost of diesel fuel has risen rapidly in the last decade. If this trend continues, railroads may find it cost-effective to reduce fuel waste by increasing attention to maintenance details. (Excessive smoke is generally a sign of poor combustion and, therefore, poor fuel economy.) The financial health of the industry will have a direct affect by allowing the replacement or retrofit of outdated equipment or necessitating the continued use of dirty engines along with currently deferred maintenance practices.

9.2.3 Interstate Commerce

At the present time, major disruptions of interstate commerce have apparently not resulted from the large number of varied standards applicable to railroad rolling stock primarily because of the widespread lack of enforcement. Some minor problems have apparently been encountered because of different opacity regulations. Naturally, these have occurred when rail operations pass from a jurisdiction with lenient or nonexistent regulations to a jurisdiction of more strict regulation or enforcement. The best example occurs between California and Nevada. In this area, it has been reported by government agencies that only "clean" locomotives proceed into California while the "dirty" units are uncoupled at the border, presumably to service shipments moving east. Although this presents logistics problems and time delays for the affected railroad, it has not created any extreme adverse effects.

Although the current situation is not of immediate concern, the potential for disruption by increased regulatory enforcement under multiple standards poses a potential threat to interstate commerce. It is not possible to predict the exact degree to which rail commerce could be curtailed. It is clear, however, that rail operations could be affected by a moderate increase in enforcement against line-haul locomotives because of the multitude of different standards and political jurisdictions.

The potential hazards of varying state and local regulations were recognized by the railroad industry and resulted in the request by the Association of American Railroads for preemptive Federal emission regulations. The request was based solely on the need to prevent disruption of interstate commerce by removing the burden of complying with a multitude of different standards.

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