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DIESEL LOCOMOTIVE EXHAUST EMISSION CONTROL AND ABATEMENT

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16. Abstract

Exhaust emissions from diesel locomotives are a product of engine design and combustion characteristics. These pollutants, control methods, and emissions reduction through engine maintenance and retrofittable equipment changes are discussed in this report.

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TABLE OF CONTENTS

	Page
1.0 INTRODUCTION	1
2.0 TYPES OF AIR POLLUTION	4
2.1 Hydrocarbons	4
2.2 Smoke	5
2.3 Carbon Monoxide	6
2.4 Nitrogen Oxides	6
3.0 DIESEL EMISSION ABATEMENT	7
4.0 ABATEMENT PROGRAMS	10
4.1 Maintenance	10
4.2 Retrofittable Modifications	10
5.0 CONCLUSION	11
6.0 RECOMMENDATIONS	12
BIBLIOGRAPHY	13
APPENDIX A	A-1
A.1 Smoke	A-2
A.2 Hydrocarbons and Carbon Monoxide	A-2
A.3 Oxides of Nitrogen	A-3

LIST OF ILLUSTRATIONS

Figure | Page

1. Idealized Curve Showing Relationship of Smoke Density to BMEP (Brake Mean Effective Pressure) for a Diesel Engine 8

1.0 INTRODUCTION

The diesel engine powers the freight industry in the United States. This includes barges, most intercity trucks, and 99% of railroad locomotives. Since the prime product of the freight industry is ton-miles and its raw material is fossilized carbonaceous fuel, it is to be expected that the industry would select an engine which would most efficiently transform fuel into ton-miles. This is, in fact, what has happened, and the diesel engine in its present form is the most efficient heat engine in production today.

The diesel engine, however, has a reputation for being smelly, smoky and noisy. This reputation in our ecology-conscious society is creating a political problem for the diesel. This is unfortunate because the smell and smoke are not necessary to efficient diesel engine operation and, with the exception of nitrogen oxides, the diesel is the least polluting of the internal combustion engines. It is probable that without this stigma, the political pressure to lower exhaust emissions and the growing awareness of our rapidly depleting oil reserves would be presently forcing the general use of diesel engines to power the private automobile. In fact, the stratified charge engine, which currently appears to be the most likely successor to the current private automobile engine, is nothing more than a gasoline burning *diesel*.

The responsibility for the specification and enforcement of air pollution standards for most mobile sources rests with EPA (Environmental Protection Agency). Railroad locomotives, however, are not covered by EPA*. This situation is not expected to last long, and the AAR (Association of American Railroads) is reported to be planning to introduce legislation for such a change. EPA, however, only has control at present over new equipment. The states have jurisdiction over equipment manufactured prior to regulation and in operation within the state. Considering the age

*Locomotives were included in the original draft of the legislation which defined E.P.A.'s jurisdiction. By the time the bill reached its final form, however, the responsibility of regulating both tracked and water borne vehicles had been deleted. It is not clear why this deletion was made.

and replacement rate of the existing locomotive fleet, uniform locomotive regulation throughout the country will also require the law to be ammended to transfer the regulation of older locomotives to EPA. Since the Federal Government has not taken the initiative in regulation and control of diesel locomotives, various state governments have begun to impose their own regulations. States with tracks at high altitudes are placing strict regulations on exhaust smoke, and states with special air pollution problems such as California are proposing regulations similar to those for highway vehicles. These regulations are often written without due regard to the engineering limitations of the diesel engine or the archaic and rapidly changing measurement techniques. It is possible that if the present system of regulation by the individual states is allowed to continue, in certain areas of the U. S. certain locomotives will be restricted to operation within specific states. A detailed description of the present regulation structure for diesel locomotives is the subject of another TSC (Transportation Systems Center) report which will be published shortly.

The population of locomotive diesel engines is an important aspect of the problem of exhaust pollution control. Their design, design diversity, maintenance cycle, and replacement cycle should all be considered in any regulation for exhaust control. 80% of the road locomotives are EMD manufactured, 2-cycle design with most parts interchangeable. The engine rebuild cycle is 5 years and the replacement cycle is 30 years. 1/3 of these engines are turbocharged. The remainder are *normally aspirated*, which usually means scavanged with a roots pump.

The railroad locomotive diesel emissions task has undertaken this year to determine the extent of the railroad's contribution to air pollution and the control methods available for this pollution abatement. This program will take several years and will provide the Federal Railroad Administration with the cost/benefit analysis necessary to both government and industry for future environmental planning and programs.

This year the railroad diesel has been studied for its potential as a low pollution source of locomotive power. Preliminary data indicates that the diesel railroad locomotive air pollution contribution is minimal and the railroad may well be the least polluting method of moving overland freight.

2.0 TYPES OF AIR POLLUTION

There are many diesel exhaust stream components which contribute to air pollution. These components are alsways broken down into the classification of hydrocarbons, smoke, CO (carbon monoxide) and NOx (nitrogen oxides). This classification is useful because it groups the pollutants in a manner which is meaningful relative to physiological hazard, asthetic values, and control and measurement techniques. It is important to understand these classes and how they interact since such an understanding is basic to control problems analysis and control techniques optimization, e.g., high hydrocarbons with high CO indicates excessively rich mixture, while high hydrocarbons with low CO indicates poor ignition.

2.1 HYDROCARBONS

The source of hydrocarbons is unburned and partially burned fuel. The actual composition of the hydrocarbon mixture depends on how unburned the fuel is. For example, at high temperatures and pressures and very low oxygen concentration, as might be found at the center of the fuel spray cone of a damaged injector, the original molecular structure of the fuel might be considerably altered and yet unburned. Low engine tempertures, poorly designed injectors, and restricted air intake are just a few of the causes of high hydrocarbons. The three generic causes of unburned hydrocarbons are poor ignition, poor fuel atomization, and an overly rich fuel/air ratio. Although poor engine design can contribute to the hydrocarbon problem – poor maintenance is usually the cause.

Historically, aldehydes have been treated as a problem separate from hydrocarbons. This was because it was felt that aldehydes were the primary cause of the diesel smell. Recent work has shown that there is only fair correlation between odor and aldehydes. Aldehydes are certainly more irritating and have a greater propensity for the formation of photochemical smog than other hydrocarbons, but most hydrocarbon regulating legislation does not recognize this fact. Aldehydes are always considered with the other hydrocarbons as will be done in this work.

2.2 SMOKE

On a weight basis, visible diesel exhaust smoke is almost entirely either fuel droplets or micron-size carbon particles. Fuel droplets form a white smoke or are a component of grey smoke. For the purposes of this report, fuel droplets are considered hydrocarbons, and are only mentioned here because most observers do not make this distinction. Carbon particles constitute black smoke or what shall be referred to as "smoke" in this report.

All the causes of high hydrocarbons, with the exception of no ignition, will also cause smoke. Smoke is partially burned hydrocarbon so mechanisms which produce partially burned (not unburned) hydrocarbons will also produce smoke. Smoke will also be produced (along with sparks) by a blast cleaning of the exhaust manifold when the throttle is increased after a prolonged idling period. A time lag between engine controls and mechanical components can cause momentary periods of smoke during throttle changes. This is particularly true of turbocharged locomotives.

The most chronic form of smoking not assoicated with poor maintenance is found in locomotives operated at altitudes over a few thousand feet. Engines tend to run richer at the reduced atmospheric pressure found at high altitudes. This is aggravated by the fact that conditions at high altitudes require the locomotive to run much of the time at full throttle, which is the richest fuel setting the engine can have.

Smoke appears to be the most benign of the exhaust pollutants discussed here, yet it is presently the one giving the railroads the most trouble. The problem is an aesthetic one whereas the untrained observer witnessing a cloud of smoke will blame all the air pollution on the smoke source. Ironically, all other things being equal, photochemical smog is reduced under high smoke conditions. Although the smoke problem may be distorted beyond what its physiological importance should demand, it is none the less real.

2.3 CARBON MONOXIDE

CO is generated when a fuel is burned without sufficient oxygen. Since diesel engines smoke long before they are stoichiometrically short of oxygen, and smoking is generally avoided, it is rare that a locomotive generates significant amounts of CO. CO emissions are not and should not be a problem with diesel electric locomotives.

2.4 NITROGEN OXIDES

NOx will eventually prove the most stubborn diesel emission to control. NOx is formed in the high temperature portions of the combustion process where oxygen is present and can be viewed as the burning of the nitrogen in the air. The bulk of the NOx formed in the engine is NO (nitric oxide) which is relatively non-toxic. The noxious NO_2 (nitrogen dioxide) is formed from the NO exterior to the engine as its temperature decreases and more oxygen is available.

NOx is reduced by reducing the combustion temperature. Lower combustion temperature implicitly means lower thermal efficiency or higher specific fuel consumption. Since a diesel has been optimized for low specific fuel consumption, the NOx is high. Lowering the NOx will almost certainly mean raising the fuel consumption per horsepower hour.

The ecological and physiological effects of NOx commonly found in the atmosphere are not well understood. Many scientists working on air pollution problems presently feel that the proposed standards for NOx are unneccessarily strict. This may mean that the NOx standards will be relaxed in the future. Political pressures, however, are to maintain the strict standards for the time being.

3.0 DIESEL EMISSION ABATEMENT

The methods of reducing exhaust emissions on large diesel engines have been mostly unexplored. The engine manufacturers are only recently considering exhaust emissions as an important design parameter. Few railroad operating proceedures have ever been adjusted to minimize exhaust pollution. Neither the railroads nor the engine manufacturers have developed a comprehensive maintenance program disigned specifically to reduce pollution. All of these techniques will to varying extents contribute to locomotive pollution abatement.

From the technological standpoint, the most satisfactory approach to the problem is to completely redesign the engine with low emissions as the only design constraint. The result would likely be a prechambered engine which has proven itself in smaller diesels to be a *clean* engine. Such an undertaking would be expensive and would take roughly 8 years. This long lead time coupled with the slow locomotive replacement rate already cited makes this abatement strategy ineffective in less than twenty years.

Changes in operating procedures, however, could be effected almost immediately with little capital investment, but possibly the operating costs will increase and the operating efficiency will decrease. Changes in operating procedures would include such items as reduction in locomotive idling time, reduction in speed changes over a route, and the use of lower sulfur fuel. The technique of pollution abatement through procedural changes has great potential, but it must be approached cautiously because its impact on individual railroads could vary widely and is hard to estimate.

Maintenance can be considered an operational procedure, but it is treated separately here because of its importance. Engine manufacturers believe that maintenance procedures can be improved

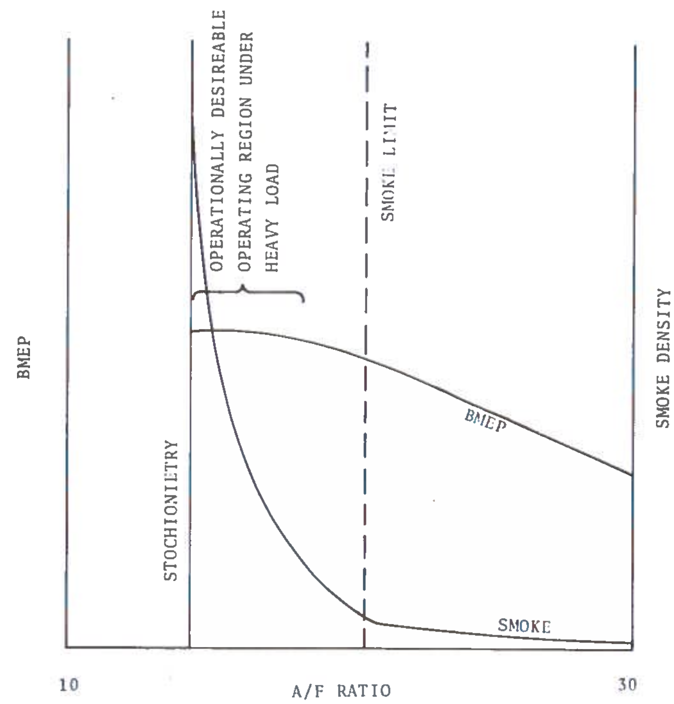

Figure 1. Idealized Curve Showing Relationship of Smoke Density to BMEP (Brake Mean Effective Pressure) for a Diesel Engine.

to reduce pollution. The diesel engine is mechanically a very durable engine. It is possible and even likely that the emission performance of an engine can degrade extensively with little noticeable loss in mechanical performance. Certain kinds of emission degradation will even improve the mechanical performance of the engine as shown in Figure 1. This raises the serious question of whether some locomotives have poor emission performance because they were optimized for mechanical performance. Improved maintenance procedures and their implementation are the first steps in reducing railroad exhaust emissions. It is unreasonable to allow the exhaust emissions of an engine to significantly exceed the design minimum for an engine just as it is unreasonable for regulations to require that exhaust emissions be reduced below that design minimum.

The ultimate in an engineering solution to the pollution problem is to design a retrofittable device which is inexpensive, eliminates exhaust pollution and otherwise leaves the engine operation unaltered. Such a device, unfortunately, will require an unforseen and improbable technological breakthrough. Improvements through retrofittable changes, however, are possible and are being made. An example of this is the recently developed low sac volume injector. Water injection and exhaust gas recirculation also appear to be useful but are not yet well developed.

The abatement methods above are described from the aspect of the effects of operational and equipment changes. Another equally valid approach to the problem is to determine the abatement techniques specific to the emission species. This approach is presented in the Appendix.

4.0 ABATEMENT PROGRAMS

4.1 MAINTENANCE

A program for collecting data relevant to maintaining low exhaust emission levels from locomotives has been discussed with the Association of American Railroads. Specifically the tasks we proposed were:

a. The collection of locomotive manufacturer's recommendation for low emission maintenance.

b. Measure the emissions before and after routine engine maintenance to determine its effect. In addition, an effort would be made to tune to minimum emissions.

c. Collecting data from locomotives which have been identified as producing excess smoke. This data would include smoke levels before and after repair and the nature of the repair.

The plan is to implement this maintenance study program on a co-operative basis with the AAR in FY73.

4.2 RETROFITTABLE MODIFICATIONS

A contract was placed with Southwest Research Institute through the Environmental Protection Agency to study methods of lowering exhaust nitrogen oxides with minimum smoke and fuel consumption penalty. The control techniques to be used will be retrofittable to most diesels presently in operation. The study will be the basis for designing equipment for a field test starting late in FY73 or FY74.

5.0 CONCLUSION

The locomotive diesel engine is relatively exhaust pollution free when it is well maintained. The two most troublesome pollution components are oxides of nitrogen and smoke. The smoke control has been improved on new locomotives by the locomotive manufacturers. Many of these improvements are retrofittable. Until the retrofit is complete and until the railroads adjust their equipment maintenance schedules to be more effective on smoke control, there are likely to be many confrontations between individual railroads and their local governments. During the interim, this will be a very serious problem for some railroads.

The techniques for the control of NOx are not so well established, and there have not yet been any engine modifications made by the manufacturers to reduce NOx. Water injection into the intake manifold presently seems to be the best method for reducing NOx with minimal degradation of efficiency, economy, power, and smoke. This technique has not yet been tried on an engine as large as is found in a railroad locomotive, but there are theoretical reasons to believe that NOx control is insensitive to engine size.

Pollution level deterioration with use would seem to be very slow. However, as with any system, the diesel will degrade with poor, incorrect, or no maintenance. Maintenance is clearly a crucial part of the locomotive pollution picture. There is little available information about the maintenance condition or procedures relative to the national locomotive fleet. A study concerning the effect of maintenance on emissions has been proposed for FY73.

The large and slowly changing locomotive inventory makes basic redesign and diesel repalcement an ineffective emission abatement method for twenty years. Any alterations in the locomotive's emissions capability must be made through components and systems which are retrofittable to most of the locomotives in the present inventory. A modest effort has been undertaken through a contractor to determine the effect of various retrofittable engine modifications and ancillary equipment.

6.0 RECOMMENDATIONS

It is recommended that the programs to study and test both, locomotive maintenance and modification outlined above be continued. If these programs cannot be implemented specifically as described above, suitable alterntives should be sought. Similar programs, with different objectives, in diesel emission control are either planned or in progress at the Office of Air Programs, Environmental Protection Agency and the Energy Research Center, Bureau of Mines. The program proposed here should be coordinated with these other programs.

The present emission standards for the freight industry are on the basis of weight of pollutant per horsepower hour. These standards were derived with a single mode (trucks) in mind. As these emission standards are applied to other freight modes such as railroads, the emission unit should be changed to reflect the thermal efficiency of the mode. The only meaningful control unit is one which measures a unit of pollution per unit of industry product. The freight industry's product is ton miles. The emissions unit for the freight industry, therefore, should be changed from grams of pollutant per horsepower hour (gm/hp hr) to grams of pollutant per ton mile (gm/ton mi). Rail freight transport thermal efficiency has a 200% to 400% advantage over truck transport. Such a change is conceptually simple, but will be difficult in practice because it will require efficiencies to be derived for each mode. This change in units, however, will tend to minimize the total pollution from the freight industry. The promotion of the grams/ton mile as the emission unit for the freight industry should be a high priority goal and may well do more for national air quality as well as assisting the railroad industry to meet emission regulations than any amount of control engineering on the diesel locomotive engines themselves.

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APPENDIX A

CONTROL METHODS FOR DIESEL LOCOMOTIVE EXHAUST EMISSIONS

A.1 SMOKE

White smoke, which is condensed fuel, appears only to be effectively controlled with an exhaust stack afterburner. White smoke is generally present only when the engine is cold as is the case when an engine is started and prior to warm up. The abatement of white smoke is a good reason for allowing diesels to idle over prolonged time periods.

Recently, injectors designed for minimum smoke have become available. This design features a low sac volume and a needle valve to precisely control the injection timing cut-off into the cylinder. These injectors should be installed at the first opportunity during normal maintenance.

Rich mixtures at high altitudes can be eliminated by having barometric controls to adjust the fuel metering system relative to the intake manifold pressure. These controls are standard on both EMD and G. E. locomotives being manufactured today, but it is not known what portion of the operating fleet uses this type of control or how effective it is. It also would be prudent for the railroads to use only turbocharged locomotives, which smoke less, in the mountains and high altitude areas. Such preventative tactics may not be an option to all railroads since it will depend on individual operator logistics and the equipment inventory.

It should be noted that, as a rule, the maximum horsepower is obtained from a diesel engine when the fuel setting is rich enough to cause moderate to heavy exhaust smoke. This fact can lead the mechanic who is adjusting the engine and has been asked to get more power from the engine to enrich the fuel settings beyond the smoke limit.

A.2 HYDROCARBONS AND CARBON MONOXIDE

The diesel engine exhaust is outstandingly low in these pollutants. However, when the engine is cold, defective, or overfueled to the extent that it is smoking, then hydrocarbons and CO emissions can be excessive. The methods of preventing these conditions are to minimize engine starts, repair defective engines promptly and adjust the engines' air/fuel ratios above the smoke limit. This last remedy will be accompanied by some loss in peak power, but it will not be excessive.

A.3 OXIDES OF NITROGEN

The most direct way to lower the NOx concentration is to lower the combustion flame temperature. This can be done by raising the specific heat of the working fluid relative to the oxygen concentration in the intake air. The most common method for doing this in internal combustion engines is to mix some of the exhaust gases with the intake air. This is done by either exhaust gas recirculation (EGR) or lowering the airbox pressure to reduce scavanging efficiency. This technique clearly lowers the volumetric efficiency of the engine and thus its peak power. There is also an increase in smoke when exhaust gases are mixed with the intake air.

The mixing of water spray with the intake air increases the specific heat of the working fluid without a significant decrease in the volumetric efficiency. This technique has worked well on diesel truck engines with the result that there was little loss in fuel economy or peak power and little increase in smoke. The effect of such a technique on engine corrosion and maintenance is not yet known.

Other possible, but less well developed techniques, include variation of the injector timing, injection rate, and valve timing.