Diesel Engines in Tunneling Operations

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Haulage in tunneling operations generally has been done with electric locomotives. As a rule, on short hauls the source of electricity is a storage battery mounted on the locomotive, which, of course, must be removed and recharged periodically. Where the distance from the recharging point to the tunnel face is very long, and where loads are heavy, trolley-driven locomotives are used. Diesel engines have been used in mining and tunneling operations in Europe for a number of years. The recent reports of studies in Belgium¹ and by the Bureau of Mines in this country²-⁴ have indicated the potentialities of this form of power for haulage, mucking, bulldozing and many other underground operations.

The hazards attending the use of Diesel engines in more or less closed spaces have long been known. The exhaust constituents that may create a harmful or objectionable environment are carbon monoxide, oxides of nitrogen and sulphur, carbon dioxide, aldehydes and smoke. Lack of precise information regarding the concentration of these gases and the ventilation requirements to reduce them to safe levels has to some extent suppressed their general acceptance in tunneling and mining work. Not until the work of the Bureau of Mines referred to above, and certain experience gained in the construction of the Delaware Aqueduct,‡ has there been available the requisite information regarding the conditions under which their use may be permitted. This paper concerns itself with the successful operation of Diesel engines underground in the construction of certain parts of the Delaware Aqueduct, and describes the conditions under which Diesel engines have been found to operate with a minimum production of noxious gases. The test data reported were obtained during the operation of Diesel engines over a period of two years.*

Studies by the New York State Department of Labor

Exhaustive tests were made by the Division of Industrial Hygiene, of the composition of the exhaust gases given off by a Diesel engine mounted on a test block. These tests showed that certain quantities of the gases are discharged from the exhaust. On the basis of these figures, preliminary requirements of design and control

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* New York State Department of Labor, Division of Industrial Hygiene, New York, N. Y.
† New York State Department of Labor, Bureau of Mines, Division of Inspection, New York, N. Y.
¹ References are at the end of the paper.
‡ The Delaware Aqueduct is a continuous hard-rock tunnel, construction of which was begun in 1937. This circular tunnel, averaging about 17 ft. in diameter and 85 miles long, when put into use will add about half a billion gallons of water daily to the New York City water supply. The use of Diesel locomotion in this work meant a great saving in time and cost to the contractors, as some of the haulage lines were as long as 35,000 feet.
* Recommendations leading to the use of Diesel engines underground were prepared by the Division of Industrial Hygiene, New York State Department of Labor, in conjunction with the Division of Mines and Tunnels of the same Bureau, the New York City Bureau of Water Supply and the U. S. Bureau of Mines. The recommendations followed upon the application of one of the Delaware Aqueduct contractors, who agreed to certain, stipulations regarding the controls described later in this paper.

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were drawn up and the use of the engines in the tunnel was permitted.

After the Diesel engine was put in operation underground, samples were taken of the air in the tunnel and determinations were made of the gases present in the tunnel atmosphere. It was found that the oxides of sulphur could be maintained at a low level if the sulphur content of the engine fuel was less than 0.5 per cent. Although small quantities of oxides of nitrogen were present in the air, they were found essentially to vary directly with the carbon monoxide content. The same was true of aldehydes.

From a study of the tunnel-air samples, the amount of carbon monoxide present was found to be a direct measure of the toxicity and the irritating properties of the atmosphere. In order to evaluate the effectiveness of the ventilation and the gas production of the Diesel engine, therefore, samples were taken of the air to determine its carbon monoxide content. The content of this gas was found to indicate fairly accurately the degree of control afforded.

The tunnel into which the Diesel engine was introduced was ventilated by a system of direct blowing. In spite of the fact that the recommended quantity of ventilation was being used, it was impossible to reduce the air contamination throughout the tunnel to a safe concentration. With the cooperation of the contractors engaged in the construction of the Aqueduct, a completely different method of ventilation was installed on this tunnel. The type of ventilation used will be discussed in another part of this paper. Studies carried on after this new system was installed showed that the recommendations set forth by the Department were somewhat inadequate and a new set of requirements was drafted.

**Design and Operation**

On the basis of preliminary studies, the New York State Department of Labor approved the use of Diesel engines in the Aqueduct subject to the conditions outlined in the requirements listed below. These requirements have been quoted by D. Harrington and S. H. Ash, of the United States Bureau of Mines, who have cooperated in this work.

**Design and Maintenance**

1. The engine fuel shall be equivalent in quality to that specified by the engine manufacturer and shall have a sulphur content not exceeding 0.5 per cent. It shall be kept in clean condition and shall be free from all foreign contaminants before being used in the engine.

2. No fuel shall at any time be stored underground except that carried in the fuel tanks of the engine.

3. The fuel injection system shall be designed and constructed so that the ratio of air to fuel cannot be reduced below 20 to 1, and the fuel pump adjustment shall be sealed.

4. An extra fuel pump set to meet the above requirements and sealed shall be furnished for each engine.

5. The engine manufacturer shall specify: (a) minimum idling engine speed, (b) maximum engine speed, (c) maximum power output.

6. The engine shall be equipped with flame arrestors on the intake and exhaust systems, of such a design that the surface temperature of the exhaust manifold shall not exceed 400°F. and the exhaust gas temperature at the point of discharge shall not exceed 160°F.

7. The engine exhaust gases shall be discharged into the atmosphere at a point remote from the engine operator.

8. The exhaust gases shall be cooled either by washing and/or spraying with water so that no incandescent particles shall be discharged into the surrounding atmosphere.

9. Spent gases from the Diesel engine shall be diluted with at least 10 times their volume of air before being released into the underground atmosphere.
contaminated by exhaust gases from the Diesel locomotive when operating between the auxiliary intake and the face of the tunnel.

3. Whenever a Diesel engine is used in underground tunnel operation, all headings shall be separately ventilated by primary exhaust ventilation. When any portion of the primary exhaust ventilation system is not functioning, no Diesel motor shall be running.

4. The auxiliary ventilating system shall be put into operation as outlined above before the men return to work at the face after blasting.

**Protective Devices Used on Diesel-engine Exhaust**

The successful operation of Diesel engines underground is contingent upon the design of control apparatus connected to the exhaust manifold. Two considerations are of greatest importance with regard to the kind of apparatus used; namely, (1) the elimination of flame, and (2) the reduction of exhaust contaminants to safe limits. The first of these is a prerequisite in gassy mines and tunnels and for soft-coal mining operations, while the second is necessary in all types of underground operations. The devices used on Diesels with which this exhaust gases is achieved by a plate device E shown in Fig. 1.

After the gases pass through the flame eliminator they are forced through a labyrinth scrubber assembly, indicated by L in Fig. 2, which is partly filled with water. As the gases pass through the scrubber, most of the noxious contaminants other than carbon monoxide are removed.

From the scrubber, the gases pass through another labyrinth (S in Fig. 2) where the moisture picked up in the scrubber is removed. Thereafter, the gases are exhausted through a muffler. The parts indicated by T and C in Fig. 2, which is essentially an activated-charcoal absorber, were not used in the Aqueduct engines.

The general arrangement of exhaust-control equipment used on the Delaware Aqueduct engines differs in some essential respects from that shown in Figs. 1 and 2. As has been pointed out in the section on Design and Operation, three important requirements are set forth: (1) control of air-fuel ratio; (2) reduction of noxious gases and (3) dilution of final exhaust discharge. The first of these was achieved by means of
10. The level of water in the storage tank shall control a valve interlocked to the fuel line which will stop the flow of fuel oil before the water supply becomes exhausted.

11. The engine shall be equipped with an electrical or other starting mechanism of sufficient capacity to permit frequent starting of the engine.

12. The carbon monoxide content of the exhaust gases leaving the engine manifold and before dilution shall not exceed 0.1 per cent.

Toxic Concentrations

1. The carbon monoxide concentration at any point in the general tunnel air shall not exceed 0.002 per cent.

2. The concentration of oxides of nitrogen at any point in the general tunnel air shall not exceed 40 parts per million.

3. The concentration of sulphur dioxide, aldehydes, visible smoke or other irritants in exhaust gases shall not create toxic or irritating atmospheric conditions or reduce visibility in the tunnel.

4. Hazardous or irritating atmospheric conditions created by the engine but not covered by the above specifications shall be brought under control as required by standards of Industrial Hygiene.

Testing

1. The engine, including the auxiliary exhaust-gas conditioning equipment, shall be tested before being taken underground and also after being placed in operation, under the conditions for which approval by the Department of Labor has been requested for a period long enough to determine its operating characteristics.

2. The engine shall be subject to weekly inspection by a technical representative of the manufacturer, who shall certify that it is being maintained in proper working condition. Such inspections shall be continued during the period of test by the Department of Labor and thereafter shall be at periods determined upon by the results of the tests.

3. No locomotive shall be used in tunnel operations which may contain explosive gas unless classed as "permissible" by the United States Bureau of Mines.

![Diagram](image-url)

**FIG. 1.—ARRANGEMENT WITH WATER DABBING DEVICE.**

- **M**, motor; **E**, exhaust-plate device placed ahead of gas-washing circuit; **L**, gas-washing box (scrubber); **S**, gas issue.

Ventilation Requirements

1. Before operating a Diesel engine underground primary exhaust ventilation at a rate of 10,000 cu. ft. per min. or more per engine and a minimum air velocity of 30 linear ft. per min. in the tunnel with the end of the vent pipe not more than 150 ft. from the face nor less than 25 ft. beyond the car changer shall be maintained. The main vent pipe opening shall be at the crown of the bore.

2. Auxiliary ventilation shall be by blowing at a rate of 3000 cu. ft. per min. or more, with the intake to this system not less than 250 ft. out by the car changer and the discharge not more than 65 ft. from the face. The minimum air velocity between the face and the exhaust main shall be not less than 10 linear ft. per min. The location of the auxiliary vent pipe shall be at the "spring line." The auxiliary vent pipe shall be metal from the air intake to the car changer; flexible pressure tubing may be used between the car changer and the face. The intake to the auxiliary system must be so located that air entering it will not be
a suitable air-fuel valve, so that the air-fuel ratio did not fall below 20 to 1 (approximately equivalent to 65 cu. ft. per min. per brake horsepower). After the valve was set it was sealed, and the arrangement was such that when the air-fuel ratio fell below the value given the engine would automatically be shut off. The second and third requirements were achieved in the following manner:

The exhaust gas leaving the engine passed through a water-jacketed manifold to an exhaust cooling box. A water spray was tapped into the box and supplied from a special tank of water by means of a pump. The water from the spray was made to travel downward through the pipe in contact with the exhaust gas leaving the exhaust cooling box. The exhaust gas was discharged into the water contained in the cooling box through the perforated pipe. The gas then passed to the top of the box, where a perforated plate and a baffle plate were interposed to stop the spray. The gas was forced into a second cooling box designed to separate the water spray from the exhaust gas by means of another series of baffle plates. After leaving the second cooling box, the gases passed into a labyrinth of berles saddle. This tended to remove the soot and oil present in the exhaust gas. The discharge from the second cooling box was relatively free of noxious contaminants and was delivered to the fan behind the radiator, where it was diluted before it passed into the general air.

**Experimental Results**

*Methods of Test.*—After preliminary testing showed that the quantities of aldehydes, oxides of nitrogen and other noxious materials were essentially contingent on the carbon monoxide content, testing for air contamination by the Diesel engines resolved itself to sampling for this gas. The instrument employed in the field for this was the widely used Hopcalite carbon monoxide indicator. This device as employed by the Department was fitted with a supersensitive scale in addition to the normal scale. The smallest division on this scale represents an atmospheric concentration of 5 parts per million (0.0005 per cent) of carbon monoxide. Samples of atmosphere were taken at three different locations: (1) in the exhaust manifold of the engine, (2) at the final exhaust of the engine (after dilution) and (3) in the tunnel air stream.
DIESEL ENGINES IN TUNNELING OPERATIONS

TABLE 1.—Results of Tests on Diesel Locomotive at Factory

<table>
<thead>
<tr>
<th>Condition of Test</th>
<th>Engine Speed, R.P.M.</th>
<th>Carbon Monoxide Concentration in Exhaust, Per Cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idling</td>
<td>530</td>
<td>0.00</td>
</tr>
<tr>
<td>Intermediate</td>
<td>700</td>
<td>0.01</td>
</tr>
<tr>
<td>High</td>
<td>900</td>
<td>0.01</td>
</tr>
<tr>
<td>High</td>
<td>1,170</td>
<td>0.01</td>
</tr>
<tr>
<td>High</td>
<td>1,600</td>
<td>0.01</td>
</tr>
</tbody>
</table>

* These samples were analyzed by the iodine pentoxide method.

Diesel Locomotives.—In cooperation with the United States Bureau of Mines, a series of tests was made on the exhaust of the locomotives. Before any Diesels were used underground, complaints from the tunnel workers were infrequent, except when locomotives began to smoke. On one investigation of such a condition, a distinct odor of exhaust gases could be detected in the tunnel air. No Diesel should be permitted underground when it smokes or is in need of repairs.

Tests on Diesel Trucks.—The Diesel engines were tested on nine trucks having capacities of 8 to 15 tons. Four of these tests are shown in Table I, and indicate that before final dilution with air the carbon monoxide contained in the exhaust gases is relatively low. These tests were made before any Diesels were used underground. Subsequently, during tunneling operations, six similar locomotives were tested underground, with results as shown in Table 2. The tests were made under widely varying conditions of tunnel ventilation but in general show less than the accepted standard for safe concentrations of carbon monoxide in air (100 p.p.m. = 0.01 per cent). Complaints from the tunnel workers were infrequent, except when locomotives began to smoke. On one investigation of such a condition, a distinct odor of exhaust gases could be detected in the tunnel air. No Diesel should be permitted underground when it smokes or is in need of repairs.

TABLE 2.—Results of Tests on Diesel Locomotives in Tunnel

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Locomotive number</th>
<th>Engine load</th>
<th>Carbon monoxide concentration, per cent:</th>
<th>Rate of air flow, cu. ft. per min.</th>
<th>Air movement, ft. per min.</th>
<th>Reactions of men</th>
<th>A</th>
<th>A</th>
<th>C</th>
<th>B</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Manifold</td>
<td>Exhaust</td>
<td>Tunnel air: maximum</td>
<td>Minimum</td>
<td></td>
<td>3600</td>
<td>15</td>
<td>50</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>Rated horsepower (1000 r.p.m.)</td>
<td>160</td>
<td>Number of cylinders</td>
<td>6</td>
<td>Capacity (tons)</td>
<td>14</td>
<td>Air-fuel ratio</td>
<td>20:1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* This sample was taken downstream of both engines, with one engine idling only 15 ft. away from sampler, and is not representative.

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TABLE 3.—Results of Tests on Diesel-driven Trucks Inside and Outside of Tunnel G

<table>
<thead>
<tr>
<th>Truck No.</th>
<th>Capacity, Tons</th>
<th>Horsepower</th>
<th>Number of Cylinders</th>
<th>Cycles</th>
<th>Where Tested</th>
<th>Grade, Per Cent</th>
<th>Carbon Monoxide in Exhaust, Per Cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>150</td>
<td>6</td>
<td>4</td>
<td>Outdoors</td>
<td>idling</td>
<td>0.016</td>
</tr>
<tr>
<td>1</td>
<td>15</td>
<td>150</td>
<td>6</td>
<td>4</td>
<td>Outdoors</td>
<td>20</td>
<td>0.015</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>150</td>
<td>6</td>
<td>4</td>
<td>In tunnel</td>
<td>idling</td>
<td>0.018</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>130</td>
<td>4</td>
<td>2</td>
<td>Outdoors</td>
<td>idling</td>
<td>0.031</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>130</td>
<td>4</td>
<td>2</td>
<td>Outdoors</td>
<td>20</td>
<td>0.045</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>150</td>
<td>6</td>
<td>4</td>
<td>In tunnel</td>
<td>idling</td>
<td>0.02</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>150</td>
<td>6</td>
<td>4</td>
<td>Outdoors</td>
<td>20</td>
<td>0.11</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>150</td>
<td>6</td>
<td>4</td>
<td>In tunnel</td>
<td>idling</td>
<td>0.015</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>150</td>
<td>6</td>
<td>4</td>
<td>Outdoors</td>
<td>10</td>
<td>0.035</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>150</td>
<td>6</td>
<td>4</td>
<td>Outdoors (closed cab)</td>
<td>20</td>
<td>0.085</td>
</tr>
</tbody>
</table>

a These trucks had been in continuous service for about 12 months.

b No discomfort noted, but visible smoke was emitted during pull up grade in tunnel.
trucks were tested in the tunnel, out of doors when idling, and when operating on a 16 per cent grade (Table 4). The trucks were used to remove blasted rock from the face of the tunnel and were required to travel up a ramp to discharge their contents on a cull pile. The engines were six cylinders and delivered 85 hp. When the trucks were operated in the main tunnel (35 ft. in diameter) they were required to travel a distance of 300 ft. The results of tests made on the final exhaust are presented in Table 4. The condition in the main tunnel was good and there was no noticeable smoke or mist. The air movement at the center of the tunnel 6 ft. above the bottom ranged from 80 to 100 ft. per minute. In Table 4, the concentrations of carbon monoxide approximates those given for the Diesel locomotive in Table 2. Another series of tests made on five trucks operating in a tunnel on 10 and 20 per cent grades is given in Table 3. These trucks, with one exception, were six-cylinder trucks rated at 150 hp.; the other truck had four cylinders with a 130-hp. rating. A few of the concentrations were high. This is attributable to the fact that the engines causing these concentrations had been in continuous service for about 10 months without extensive overhaul.

**Bulldozer Tests.**—The bulldozer tests were made on a caterpillar tractor driven by a six-cylinder Diesel engine rated slightly over 100 hp. The tests were conducted in a tunnel supplied with 10,000 cu. ft. of air. The concentrations of carbon monoxide obtained in the breathing zone of the operator and in the final exhaust of the engine are shown in Table 5. The concentrations in the tunnel air were relatively low.

**Table 5.**—Results of Field Tests Made on Diesel-driven Caterpillar Bulldozers.*

<table>
<thead>
<tr>
<th>Engine load</th>
<th>A</th>
<th>A</th>
<th>D</th>
<th>P</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine No.</td>
<td>Idle</td>
<td>Pull (16 per cent grade)</td>
<td>Pull</td>
<td>Pull</td>
<td>Idle</td>
</tr>
<tr>
<td>Carbon monoxide concentration per cent:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manifold</td>
<td>0.017</td>
<td>0.017</td>
<td>0.012</td>
<td>0.012</td>
<td>0.012</td>
</tr>
<tr>
<td>Exhaust</td>
<td>0.005</td>
<td>0.005</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Tunnel air</td>
<td>0.12</td>
<td>0.012</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
</tbody>
</table>

* No smoke or discomfort expressed by workers or noted by investigators.

**SUMMARY AND CONCLUSIONS**

The Labor Department has conducted extensive hygienic studies on Diesel engines under actual operating conditions in tunnels. Trucks, bulldozers, and locomotives driven by these engines have been tested during all typical tunneling operations. They have operated from both shafts and portals and in dead-end runs and tunnels open at each end.

The conclusions that can be drawn from the test data obtained during these studies can be summarized as follows:

1. Diesel-powered machinery can be safely and satisfactorily used underground if careful adherence to certain strict regulations is maintained.
2. The New York State Labor Department has issued such regulations to govern the use of Diesel engines in underground operations in New York State.
3. During all types of operating conditions, these regulations have been found to stand the test of practical application and adequate control.

4. The first section of requirements covers the design and maintenance of the engines. The main points of this section are: (a) 20:1 minimum air-fuel ratio, (b) the exhaust gases must be cooled and scrubbed, (c) before discharge the exhaust must be diluted at least 10 times.

5. The second section covers allowable limits of contamination. Careful correlation of all factors has shown that the control of carbon monoxide to the set limit of 0.002 per cent affords adequate control of all noxious element.

6. The third section is devoted to requirements of ventilation, which have been found adequate to provide the required control. The governing factor in this section requires that a minimum of 10,000 cu. ft. per min. of mechanical ventilation be maintained in any area for every engine that is or may be operated in that area.

REFERENCES