AIR POLLUTION IN ROAD TUNNELS

BY

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As a part of a study of pollution of the air by motor vehicles, measurements have been made in two London road tunnels during periods of high traffic density. The concentrations of smoke and polycyclic hydrocarbons found there are much higher than the average values in Central London, but they are of the same order of magnitude as those occurring during temperature inversions on winter evenings when smoke from coal fires accumulates at a low level.

An attempt has been made to relate the concentration of each pollutant to the type and amount of traffic. Both diesel and petrol vehicles make some contribution to the amounts of smoke and polycyclic hydrocarbons found in the tunnels, but in the case of smoke, fluoranthene, 1:2-benzpyrene, pyrene, and 3:4-benzpyrene, the concentrations appear to be more closely related to the density of diesel traffic than to that of petrol traffic. The concentrations of lead and carbon monoxide have also been determined, and these are very closely related to the density of petrol traffic. During the morning and evening rush hours the mean concentration of carbon monoxide was just over 100 p.p.m. and peak values up to 500 p.p.m. were recorded at times. Oxides of nitrogen were determined in some of the experiments and there was always much more nitric oxide than nitrogen dioxide. Eye irritation was experienced but its cause was not investigated.

The concentration of pollution in the tunnels does not appear to be high enough to create any special hazards for short-term exposures. The atmosphere at peak periods may become very dirty and unpleasant and the concentration of carbon monoxide would be sufficient to produce some effect over a period of several hours' continuous exposure. The total emission of pollution from road vehicles must still be small in comparison with that from coal fires, but the effect of traffic on the concentration of smoke, polycyclic hydrocarbons, carbon monoxide, and lead in the air of city streets deserves continued study.

Although the combustion of coal is still responsible for most of the air pollution in British towns, the contribution made by motor vehicles deserves careful attention. In an earlier paper (Commings, Waller, and Lawther, 1957) the concentrations of smoke and polycyclic hydrocarbons in two London diesel bus garages were compared with those in the outside air. In each case there was much more black smoke inside the garage than outside, but the differences in 3:4-benzpyrene concentration were small. The buses were in excellent mechanical condition and they were being run under minimal load. The results of this investigation were relevant to the health of the workers in the garages, but they were of strictly limited value in any study of the possible effects on the general population of pollution from vehicles.

The highest concentrations of pollution from motor vehicles occur in tunnels, and to study the

emissions from mixed traffic, measurements were made in two London road tunnels under the Thames. Our earlier experiments had shown that the smoke from buses contains much lower proportions of polycyclic hydrocarbons than domestic coal smoke, and to avoid any interference from the latter the experiments were confined to warm days during the summer months.

Sampling Sites

The Blackwall and Rotherhithe tunnels carry all types of traffic, including regular bus services, private coaches, lorries, cars, and motor cycles. They are open also to pedestrians and cyclists, but are little used by them. Cleaning and maintenance staff spend limited periods in the tunnels and any major work is done when there is little traffic. There is no routine traffic control in either tunnel.

FIG. 1.—Section through Blackwall Tunnel, showing ventilation system.

At the time of these studies the Blackwall Tunnel was normally busier than the Rotherhithe and, because higher pollution was expected, most of our measurements were made there. There are corners and gradients to be negotiated in each tunnel and driving conditions are similar to those in highly congested streets. The composition of the traffic varies with the day of the week and with the time of day, and we took advantage of this fact to try to assess the separate contributions of petrol and diesel traffic to the pollution of the tunnel atmosphere. At all times there are fewer diesel than petrol vehicles, the proportion varying between about 2% on Sunday evening to over 30% at noon on weekdays.

The Blackwall Tunnel (Fig. 1) is 1,490 yards long and it connects the busy dock area around Poplar with Greenwich and the roads to the Kent coast. When opened in 1897 it was ventilated by four shafts, each 46 ft. in diameter, but fans had to be installed in them at intervals between 1922 and 1940 as the volume of motor traffic increased. The fans can be operated separately, but usually all are in use throughout the day, some are switched off in the evening, and all are off at night. The main requirement is to keep the concentration of carbon monoxide within reasonable limits, but this is sometimes difficult during prolonged hold-ups and drivers are warned to switch off their engines in these conditions. Smoke haze is usually visible in the tunnel and the atmosphere is often irritant to the eyes. Fresh air is ducted to the centre of the tunnel and also enters at the ends. The extractor fans in shafts 1 and 4 draw air from each direction, but in practice the section between the centre of the tunnel and shaft 4 is poorly ventilated. The maximum emission of pollution occurs near the bends at the foot of each shaft, where large vehicles often have to halt and then pull away up the inclines. Strong winds blowing into the ends of the tunnel can alter the pattern of ventilation, but pollution appeared to be highest between shafts 3 and 4 or between 1 and 2. The sampling points were sited in one of the sections having high smoke pollution, their exact position being dictated by considerations of safety and accessibility. In the first series of experiments (1958) the

samplers were placed on a shelf 7 ft. above pavement level at a point A (Fig. 1), and in the second series (1959) they were placed on a similar shelf at point B.

The Rotherhithe Tunnel is 1,620 yards long and it connects Stepney and Bermondsey. It was opened in 1908 and fans were installed between 1924 and 1932. The general layout is similar to that of the Blackwall Tunnel, but the bends do not seriously interfere with the flow of traffic. During the period of this study the Blackwall Tunnel was closed throughout some week-ends whilst alterations were being made to the approach road, and the Rotherhithe Tunnel then carried much extra traffic. On one of these occasions samples were taken there at a point between two of the shafts, where pollution was high, using a shelf mounted 7 ft. above pavement level as in the Blackwall Tunnel.

The pollution problems encountered in these tunnels during the period 1928 to 1931 when the ventilation systems were being redesigned have been discussed by Regan (1932).

Traffic Counts

Throughout each of the experiments the flow of traffic was determined by observers standing inside or just outside the tunnel. The counts were divided into consecutive 10-minute periods, figures for each direction being recorded separately, but for most purposes the results were later expressed as vehicles per hour in either direction. Initially the vehicles were classified as "private" or "commercial" to give some indication of the proportion of petrol and diesel vehicles. Virtually all private vehicles have petrol engines and more detailed counts showed that approximately 50% of the commercial vehicles using the tunnel had diesel engines. After studying the types of vehicles in common use and drawing up a list of features to aid rapid recognition of diesel vehicles it became possible to count "petrol" or "diesel" directly and all the figures in Tables 1 to 4 have been expressed in this form.

Experience soon showed that the flow of traffic did not provide an adequate index of the emission of pollution in the tunnel. This is likely to vary with the number of vehicles in the tunnel at a given instant

and there may be a high traffic density even if the flow in vehicles per hour is low or nil. The most relevant parameter appeared to be the number of vehicles within the ventilation section in which we were working. In some experiments this was measured directly by observers stationed at each end of the section, who were in contact by telephone. When an easily recognizable vehicle passed one observer, he sent a message to the second observer who then counted and classified all vehicles passing him until the "marker" vehicle reached him. To avoid possible bias due to the selection of diesel vehicles as markers this technique was abandoned for purposes of defining the composition of the traffic. In general, it was simpler to time vehicles over the section. When necessary this was done by the two observers connected by telephone but often it was possible for one observer to walk alongside the vehicles or to stand half-way watching vehicles entering and leaving the section. The timings were made frequently and each direction was recorded separately in the first instance. From these figures mean times were calculated for each sampling period. The ventilation section considered here was that between shafts 1 and 2 (146 yards) when sampling at point A and between shafts 3 and 4 (201 yards) when at B. An estimate of the traffic density during each period was then obtained by multiplying the flow in vehicles per hour by the mean time in fractions of an hour taken to traverse the section. Results of the later experiments showed that this provided a useful statistic, although it did not take into account any variations in the emission of pollution with running conditions. The speeds of the vehicles were calculated from the times and the mean figures are quoted in Tables 1 to 4.

Procedure

During the summer of 1958 four visits were made to the Blackwall Tunnel and one to the Rotherhithe Tunnel. Congestion appeared to be greatest during the morning rush hour and samples were taken at this time on July 3 and August 20. An evening rush hour (August 1) was also studied, for there was at that time a greater proportion of petrol-engined traffic. The proportion may have been higher than on an average evening since it was the Friday before a Bank Holiday week-end. In an attempt to study almost "pure" petrol traffic further samples were taken during the late evening on Bank Holiday, August 4, when thousands of cars were returning from the coast. The traffic was fairly fast on this occasion, for it was mainly in one direction and there were few large vehicles to cause obstruction at the bends. There were some diesel buses and coaches but few lorries. All the samples up to this time were collected

at point A (Fig. 1). A similar sample was taken in the Rotherhithe Tunnel on September 14 when the Blackwall Tunnel was closed and there were again thousands of cars returning from the coast on a warm Sunday evening.

An analysis of the results of these preliminary experiments showed that there was a general relationship between the concentration of each pollutant and the density of traffic, but the large number of variable factors precluded any attempt to discriminate between the effects of petrol and diesel traffic. Big differences in the type or amount of traffic were attended by big differences in speed, and variations in wind speed and direction from one day to another were sufficient to cause differences in ventilation rate at our sampling point.

Further experiments were deferred until the summer of 1959, but in the meantime additional traffic counts were made and the pattern of pollution along the tunnel was checked visually on a number of occasions. High pollution was encountered more often at the southern end of the tunnel than at the northern, and the sampling shelf was moved to point B (Fig. 1).

To minimize the effects of variations in ventilation rate a series of experiments was planned for a single day when there was a steady wind. It was found that on a normal week-day the number of diesel vehicles using the tunnel reached a maximum towards midday and the number of petrol vehicles was highest around 6 p.m. Arrangements were therefore made to sample continuously from 10 a.m. until 7 p.m. so as to include these two peaks. To avoid interference from domestic smoke the experiment was scheduled for a very warm day when few fires would be in use. The weather became fine and warm in early May and the experiment was carried out on Thursday May 14 when the outside temperature reached 70°F. and the wind remained steady at about 5 m.p.h. from a north-easterly direction. An intensive study of pollution was made on this occasion and a team of four observers timed and counted traffic continuously. There would have been some advantage in continuing for a complete 24-hour period, but the experiments proved to be very arduous under the conditions in the tunnel, and with the staff available it was not practicable to continue any longer.

A final experiment was planned to cover an overnight period which we had not previously studied. This was started during the evening of Sunday July 5, one of the hottest days of the year, and lasted until 10 a.m. on Monday. We were thus able to examine the pollution caused by a period of very heavy traffic, consisting mainly of private cars returning from the coast, followed by a quiet period during

TABLE 1
RESULTS OF TUNNEL EXPERIMENTS, SUMMER 1958

Time	Blackwall Tunnel								Rother- hithe Tunnel	Merton Garage
	July 3, 1958		August 1, 1958			August 4, 1958	August 20, 1958		September 14, 1958	June 21, 1956
	08-45-09-45	09-50-10-50	16-00-17-15	17-33-18-33	18-38-19-38	19-30-22-00	08-30-09-36	09-38-10-32	21-00-22-42	23-00-01-00
Traffic flow*: Petrol	919	631	1,037	1,228	1,054	1,552	1,136	896	1,439	—
Diesel	272	233	228	210	140	55	335	312	125	—
Speed (m.p.h.)	—	—	—	1.7	2.9	4.1	2.0	2.8	16.2	—
Traffic density†:										
Petrol	—	—	—	60	30	31	47	26	20	—
Diesel	—	—	—	10	4	1	14	9	2	—
Carbon monoxide (p.p.m.)	295	—	—	200	—	138	—	70	170	—
Smoke (mg./100 m. ³)	235	174	133	162	116	93	157	179	191	144
Hydrocarbons, µg./100m. ³ air:										
Fluoranthene	73	66	29	38	21	42	35	27	54	10
1 : 2-benzpyrene	19	16	9	16	10	11	11	12	17	2
Pyrene	119	100	43	62	30	60	52	39	81	17
Coronene	35	33	17	34	25	22	22	21	30	—
Anthanthrene	16	17	6	17	12	13	11	9	18	—
1 : 12-benzperylene	53	53	19	57	42	36	40	37	55	2
3 : 4-benzpyrene	29	26	14	24	12	18	17	16	27	3
Hydrocarbons, µg./g. smoke:										
Fluoranthene	308	381	216	233	184	434	225	151	283	69
1 : 2-benzpyrene	80	95	69	98	87	117	71	68	89	17
Pyrene	505	578	324	387	257	628	328	216	425	120
Coronene	150	191	125	213	215	228	142	116	155	—
Anthanthrene	67	97	44	102	106	132	70	52	94	—
1 : 12-benzperylene	225	307	140	352	361	377	352	208	295	13
3 : 4-benzpyrene	123	151	109	146	101	186	111	91	141	18

*Vehicles per hour in both directions.

†Estimate of number of vehicles in relevant ventilation section (see text).

the night after which there was the morning rush hour. The flow of cars continued well into the night, but our hopes of sampling "pure" petrol engine pollution at that time were spoilt by the presence of a number of diesel-engined coaches. The wind remained steady at about 9 m.p.h., from a northerly direction during the course of the experiment, but there were some big changes in ventilation when the fans were switched off during the night.

In each of these experiments samples of smoke were taken, usually over periods of one hour, for the determination of polycyclic hydrocarbons, and in the later series (1959) part of each sample was used for the determination of lead. A continuous record of the carbon monoxide concentration was obtained on two occasions (September 14, 1958 and May 14, 1959) and "spot" measurements were made at other times. Oxides of nitrogen were also measured during some of the experiments, but no observations were made on sulphur dioxide. Since the tunnel air enters from four widely separated points it was considered impracticable to define completely the background level of pollution. All the measurements were made at times of very low background pollution and results from observations in Central London were available for comparison.

Sampling and Analytical Methods

The methods used were similar to those employed in the earlier experiments in bus garages (Commins *et al.*, 1957). Samples of smoke were collected on weighed glass fibre filter sheets measuring 8 in. by 10 in. overall, using a Staplex high volume sampler. Each filter, after weighing, was extracted with cyclohexane for three hours in a Soxhlet apparatus and the yellow extract was reduced to small volume and transferred to a column of alumina. The hydrocarbons were separated chromatographically by elution with cyclohexane and determined spectrophotometrically (Commins, 1958).

Where lead was determined, the filter was divided and a measured fraction of it extracted with nitric acid; an aliquot of this solution was extracted with a small excess of dithizone in chloroform and the excess dithizone removed by washing with ammonia-potassium cyanide solution (Harrold, Meek, and Holden, 1936). The amount of lead in the extract was estimated colorimetrically by a comparison of the red colour of the lead-dithizone complex.

A recording infra-red analyser was used to determine carbon monoxide in the tunnel. Spot samples were collected in evacuated bottles and analysed later in the laboratory.

Oxides of nitrogen were collected by passing the tunnel air through sintered bubblers containing absorbing reagent (Saltzman, 1954). Nitrogen dioxide was absorbed

first and the nitric oxide was then oxidized and collected as NO_2 (Thomas, MacLeod, Robbins, Goettelman, Eldridge, and Rogers, 1956). In the 1959 experiments samples were taken over hourly periods and the colorimetric determinations were made in the tunnel; in some earlier experiments "spot" samples were collected in evacuated bottles and analysed in the laboratory.

Results

The results from each of the experiments carried out during 1958 have been assembled in Table 1. The concentration of "smoke" (including all particulate matter collected by the high volume sampler) ranged from 93 to 235 mg./100 m.³. This is many times the concentration in the ordinary London air at that time of year; samples collected by the same method in Central London at intervals throughout the summer gave results ranging from 10 to 26 mg./100 m.³. To allow some comparison to be made with our earlier bus garage experiments, results from the mid-summer experiments at Merton have been included in this Table. The figures quoted here refer to the period between 11 p.m. and 1 a.m., when the smoke from the buses was sufficient to raise the concentration in the garage to several times the outside level. Under these conditions there was little error in considering the buses to be responsible for all the pollution in the garage, and direct comparisons can be made with the tunnel results. The concentration of each hydrocarbon is much higher in the tunnel than in the garage, but in view of the differences in ventilation little can be inferred from these figures alone. More useful is the comparison of the composition of the smoke, expressed as micrograms of hydrocarbon per gram of smoke. In this respect also the tunnel results are much higher than those obtained in the garage. This suggests that the petrol and diesel vehicles using the tunnel are producing smoke which is richer in hydrocarbons than that emitted by diesel buses when manoeuvring in garages.

The concentrations of pollutants recorded in this series do not vary consistently with the type or amount of traffic, but the smoke concentration was lowest on the Bank Holiday when there were few diesel vehicles present. The concentrations of most of the hydrocarbons at that time were, however, similar to those obtained on other occasions.

The concentration of carbon monoxide observed during the course of these experiments was generally greater than 100 p.p.m. Most of the samples were collected in evacuated bottles over brief periods, but the result quoted for the Rotherhithe Tunnel is an average value over the one and three-quarter hour period of the main experiment. The infra-red

analyser was left running for two days before and one day after this experiment. The record showed a further increase in concentration after we had left on the Sunday night, reaching a peak of 500 p.p.m. at midnight. High concentrations were also recorded on the Friday evening, with peak values of 450 p.p.m., and again on Saturday evening, with values up to 340 p.p.m.

Several samples were also collected in evacuated bottles for the determination of oxides of nitrogen, but difficulty was experienced in preventing oxidation of nitric oxide before the determinations were made. Concentrations of nitric oxide ranged from 1 to 8 p.p.m., with smaller quantities of nitrogen dioxide. In later experiments continuous samples were taken and the determinations were made in the tunnel.

Detailed results from the hourly samples taken on May 14, 1959 at point B are given in Table 2. The concentration of smoke varied between 169 and 319 mg./100 m.³, approximately 10 times that in the air of Central London at that time. The concentrations of smoke and of each of the hydrocarbons were in general higher than those encountered in the earlier experiments at the other end of the tunnel (point A). The concentration of carbon monoxide was measured continuously and peak values of up to 235 p.p.m. were recorded. The results for oxides of nitrogen show a much lower ratio of nitrogen dioxide to nitric oxide than is found in the ordinary atmosphere. The concentration of nitric oxide remained close to 1 p.p.m. throughout these experiments, but there was always less than 0.1 p.p.m. of nitrogen dioxide. There was much more lead in the tunnel than occurs normally in urban atmospheres. The concentrations were of the same order of magnitude as those found by Preis (1957) in a road tunnel in Zürich.

In Fig. 2 the relationship between the concentrations of pollutants and the traffic density is shown graphically. All values have been plotted as percentages of the mean for each series so that hour-to-hour variations can be studied on a common basis. The densities of petrol and diesel traffic follow one another fairly closely during the earlier part of the day but in the evening there is a sharp difference between them. The curves have been grouped so as to separate those which show a pronounced rise during the evening from those which do not. The lead and carbon monoxide graphs (Fig. 2) certainly belong to the former category, and follow very closely that for the density of petrol traffic.

Tetra-ethyl lead is added to most petrol, and fine particles containing lead sulphate, lead bromide, and other compounds are emitted with the exhaust gases (Dettling, 1957); diesel fuel does not contain any

FIG. 2.—Variation in traffic density and concentration of pollutants in Blackwall Tunnel, May 14, 1959.

appreciable quantity of lead. Petrol engines also produce much more carbon monoxide than diesel engines (Fitton, 1958). We would therefore expect the concentrations of lead and carbon monoxide to vary with the amount of petrol traffic, and the similarity between the curves suggests that the density of petrol traffic is in fact a useful index of pollution from petrol-engined vehicles. The curve for coronene has also been included in this series, for it shows some rise in the early evening; the concentration of 1:12-benzperylene also varies in a similar fashion.

The concentration of smoke (Fig. 2) does not follow the density of diesel traffic very closely, but the association is certainly closer than with the density of petrol traffic. Since the emission of smoke varies widely with load it may be that the density of the traffic does not provide an adequate index of

pollution in the case of diesel vehicles, but it would be difficult to define the operating conditions in the tunnel sufficiently to produce a better one. Variations in the concentration of pyrene and 3:4-benzpyrene are also shown in Fig. 2 and the concentrations of fluoranthene and 1:2-benzpyrene follow similar patterns. The concentration of anthanthrene varies rather irregularly.

The quality of the smoke can also be considered from the second part of Table 2. The amounts of most of the hydrocarbons (in μg . per gram of smoke) were similar to those found in the earlier experiments, though it can be seen that there is a tendency for the proportions of coronene and 1:12-benzperylene in the smoke to increase with the proportion of petrol traffic.

It seems likely from the figures presented so far

TABLE 2
POLLUTION IN BLACKWALL TUNNEL, MAY 14, 1959

	Time (hours)								
	10-	11-	12-	13-	14-	15-	16-	17-	18-19
Traffic flow*: Petrol	702	674	611	631	756	780	1,018	1,241	1,196
Diesel	346	362	326	284	324	311	286	211	194
Speed (m.p.h.)	5.5	7.4	11.1	9.1	6.0	8.7	7.9	5.4	6.3
Traffic density†: Petrol	14.6	10.3	6.3	7.5	14.3	10.2	14.7	26.2	21.6
Diesel	7.2	5.5	3.4	3.4	6.1	4.1	4.1	4.5	3.5
Carbon monoxide (p.p.m.)	76	64	39	35	81	66	92	120	103
Smoke (mg./100 m. ³)	268	319	216	169	200	177	204	202	177
Lead (µg./m. ³)	23.8	18.7	11.4	9.2	18.8	13.4	19.0	27.2	22.0
Nitric oxide (p.p. 100 m.)	87	133	97	91	137	103	80	121	103
Nitrogen dioxide (p.p. 100 m.)	3	10	7	6	7	7	5	10	7
<i>Hydrocarbons, µg./100 m.³ air:</i>									
Fluoranthene	160	125	109	84	95	81	94	110	79
1 : 2-benzpyrene	24	24	17	14	19	13	17	18	16
Pyrene	139	137	83	66	82	68	80	98	73
Coronene	20	14	7	5	17	10	13	22	21
Anthanthrene	15	26	10	12	9	9	11	7	6
1 : 12-benzperylene	48	40	24	15	41	26	31	51	45
3 : 4-benzpyrene	47	47	32	27	33	23	29	31	27
<i>Hydrocarbons, µg./g. smoke:</i>									
Fluoranthene	597	393	505	495	474	458	465	547	448
1 : 2-benzpyrene	88	75	78	80	94	76	83	89	89
Pyrene	519	430	385	388	408	382	394	487	415
Coronene	75	44	34	27	87	55	64	109	117
Anthanthrene	57	83	48	73	47	50	55	36	35
1 : 12-benzperylene	178	126	111	87	206	148	151	252	252
3 : 4-benzpyrene	176	147	148	157	166	128	142	151	153

*Vehicles per hour in both directions.

†Estimate of number of vehicles in relevant ventilation section (see text)

that both petrol and diesel traffic make some contribution to the concentrations of each of the hydrocarbons determined in the tunnel air, but that the influence of petrol traffic is more pronounced in the case of coronene and 1 : 12-benzperylene than in the others.

Results from the overnight experiment carried out in July 1959 are shown in Table 3. The concentration of smoke varied widely, falling to a minimum of 21 mg./100 m.³ during the middle of the night and reaching a maximum of 182 mg./100 m.³ during the morning rush hour. The mean concentration in Central London at that time was approximately 24 mg./100 m.³. No measurements of carbon monoxide or oxides of nitrogen were made during this series, but the concentrations of lead were determined for each hourly period.

The concentrations of pollutants cannot be related directly to the traffic densities throughout the 14 hours of this experiment, since the ventilation rate was varied during the night. The fans in shafts 2, 3, and 4 were switched off at 23.15 hours as the amount of traffic began to decline, and they were switched on again at 06.30 hours. Those in shaft 1 were switched off at 01.00 hours and on again at 05.30 hours. Around midnight the ventilation still appeared to be satisfactory at the sampling point, even with only one set of fans in operation, but there

was a temporary increase in pollution soon after 01.00 hours when all the fans were off. Some brief periods of high pollution were also noticed shortly before all the fans were switched on again in the morning.

Broad comparisons can be made between the first three hours of the experiment and the last three. The density of petrol traffic was similar during these two periods, but there was great variation in the density of diesel traffic. The concentrations of smoke and of each of the hydrocarbons were higher when there were more diesels, and this is in accordance with earlier results, but the concentration of lead was also somewhat increased. Since lead is emitted only by petrol engines this unexpected finding may indicate that there were changes in ventilation due to varying winds or that the intermittent traffic flow during the morning period gave rise to a greater emission of lead per unit petrol vehicle than the smoother flow during the evening.

In general the smoke from this series contained smaller amounts of hydrocarbons (expressed as µg. per g.) than that collected in the earlier daytime experiment. This means either that the vehicles were emitting material which was weaker in hydrocarbons than before, or that a greater amount of extraneous dust was being picked up on the second occasion.

Particle Size Distribution of the Smoke

During the course of the study observations were being made on the size and shape of particles in the atmosphere of London, and a number of samples were collected for this purpose in the Blackwall Tunnel. The samples were collected on formvar films in a thermal precipitator and examined on an electron microscope. Nearly all the particles were small smoke aggregates, with a mass median diameter of approximately $1\ \mu$ (Waller, Brooks, and Cartwright, 1961). The form of the particles was typical of those produced by the incomplete combustion of hydrocarbon fuels. All were small enough to stay in suspension indefinitely and they were well within the respirable size range.

Discussion

The primary object of this investigation was to assess the magnitude of the problem of air pollution by motor traffic and in order to do this we worked in the most polluted places we could find. In these two tunnels we were able to study pollution by petrol and diesel vehicles in widely varying mechanical states and operating conditions, and the main object of the study has been achieved. As our work progressed we began to hope that by comparing the pollution during selected periods of diverse traffic composition we might be able roughly to identify the main sources, petrol or diesel, of individual

pollutants. In this secondary aim we were only partially successful and the apparent correlations between the concentrations of various pollutants and the type and amount of traffic must be interpreted with great caution. The Blackwall Tunnel has two bends which tend to impede large vehicles (which are mostly diesel powered) and thus radically alter the flow of traffic; a curious consequence of this impedance is that large diesel vehicles can seem to emit lead by holding up petrol traffic. This obviously false relationship between the nature of traffic and one pollutant serves to sound a note of caution when we consider the emission of other pollutants, the source of which is not known with the same certainty. No account has been taken of variations in types of vehicle within the general categories of "petrol" and "diesel"; during the day-time there is a large proportion of commercial traffic and the emissions from diesel or petrol engined lorries may differ from those of the buses or cars which make up the bulk of the traffic at other times. Over a limited period however the concentrations of both lead and carbon monoxide in the tunnel air vary with the amount of traffic, and the results from the experiment carried out on May 14, 1959 show a real relation between the concentrations of these pollutants and the density of petrol traffic, which must then be considered as an important source of carbon monoxide and lead compounds. Industrial

TABLE 3
POLLUTION IN BLACKWALL TUNNEL, JULY 5-6, 1959

	Time (hours)													
	20-	21-	22-	23-	24-	1-	2-	3-	4-	5-	6-	7-	8-	9-10
Traffic flow*:														
Petrol	1,265	1,321	1,481	1,292	632	155	34	30	40	197	618	1,072	1,006	838
Diesel	49	49	39	27	24	17	7	11	14	76	221	327	367	335
Speed (m.p.h.)	9.5	10.5	17.8	18.6	22.7	29.2	29.2	21.5	24.1	21.5	17.0	6.1	10.2	6.1
Traffic density†:														
Petrol	15.1	4.31	9.5	7.9	3.2	0.6	0.13	0.16	0.19	1.04	4.12	20.0	11.2	15.6
Diesel	0.59	0.53	0.25	0.17	0.12	0.07	0.03	0.07	0.07	0.40	1.47	6.09	4.08	6.24
Smoke (mg./100 m. ³)	46	59	45	44	32	41	21	24	55	112	147	182	159	159
Lead (μg./m. ³)	11	17	11	14	8	15	3	5	6	11	21	20	22	22
Hydrocarbons μg./100 m. ³ air:														
Fluoranthene	7.9	17.3	11.2	3.9	3.9	7.6	2.8	1.5	1.4	17.4	35.1	40.0	34.6	34.6
1 : 2-benzpyrene	3.6	6.7	4.7	2.5	2.7	2.9	0.8	1.1	0.8	5.6	10.7	11.7	12.5	12.5
Pyrene	6.4	13.6	8.5	3.7	2.9	7.4	1.9	1.2	1.2	15.6	37.1	38.4	35.8	35.8
Coronene	5.7	8.2	3.8	3.9	3.3	3.9	0.6	1.3	0.9	4.1	14.6	16.7	19.3	19.3
Anthanthrene	0.8	4.4	2.1	1.3	1.2	3.2	0.3	0.6	0.2	2.7	9.8	10.2	11.5	11.5
1 : 12-benzperylene	9.7	17.4	9.5	8.9	7.2	9.7	1.8	3.2	2.0	11.7	35.5	36.6	41.6	41.6
3 : 4-benzpyrene	5.8	13.5	8.0	3.9	4.4	4.5	1.5	1.6	1.5	7.8	13.8	17.7	16.5	16.5
Hydrocarbons μg./g. smoke:														
Fluoranthene	172	290	253	89	121	185	134	64	26	156	240	19	216	216
1 : 2-benzpyrene	78	113	106	57	83	71	40	45	15	50	73	264	78	78
Pyrene	137	229	192	83	89	179	94	48	21	140	253	211	224	224
Coronene	124	138	86	88	103	94	29	55	16	36	100	91	121	121
Anthanthrene	17	73	47	29	37	56	14	26	4	24	67	56	72	72
1 : 12-benzperylene	210	293	216	201	224	236	90	133	36	105	242	207	260	260
3 : 4-benzpyrene	126	227	181	87	135	110	75	68	27	70	94	97	103	103

*Vehicles per hour in both directions.

†Estimate of number of vehicles in relevant ventilation section (see text).

TABLE 4
POLLUTION IN BLACKWALL TUNNEL, SUMMARY OF RESULTS

	Blackwall Tunnel					Central London		
	Morning Rush Hour	Evening Rush Hour	Daytime	Holiday Evening	Night Minimum	Typical Summer	Typical Winter	Temperature Inversions
Petrol vehicles per hour	921	1,129	692	1,454	30	—	—	—
Diesel vehicles per hour	306	212	326	50	11	—	—	—
Speed (m.p.h.)	5	4	8	9	22	—	—	—
Smoke (mg./100 m. ³)	178	166	225	72	21	20	35	670
Lead (μg./m. ³)	21	23	16	13	3	1	2	5
Carbon monoxide (p.p.m.)	132	105	60	138	—	17*	11*	360†
Hydrocarbons (μg./100 m. ³)								
Fluoranthene	46	62	109	27	2.8	1.0	2.5	407
1 : 2-benzpyrene	14	14	18	8	0.8	0.8	2.0	74
Pyrene	64	64	96	35	1.9	1.0	2.5	317
Coronene	24	22	12	14	0.6	0.4	1.0	28
Anthanthrene	12	10	14	8	0.3	0.2	0.5	38
1 : 12-benzperylene	43	40	32	24	1.8	0.8	2.5	106
3 : 4-benzpyrene	20	23	35	14	1.5	1.2	5.0	222

*Mean of street concentrations reported by Wilkins (1956).

†Highest value in series of instantaneous samples taken in busy streets.

and domestic chimneys also emit carbon monoxide and small quantities of lead but these sources are unlikely to contribute significantly to the concentrations occurring amongst heavy traffic. Brief, Jones, and Yoder (1960) have reported close correlations between the concentrations of these pollutants and the amount of traffic in the streets of a north-eastern United States city. These authors did not distinguish between petrol and diesel traffic, but the latter probably formed only a small percentage of the total. In Central London a substantial proportion of the traffic has diesel engines which can be discounted as emitters of lead and carbon monoxide. Our work in streets, garages, and tunnels leads us to support the suggestion of Wilkins (1956) that the current use of diesel engines in buses and heavy goods vehicles provides one explanation for the lack of any substantial increase in carbon monoxide concentrations in London streets over a period of 24 years, despite large increases in traffic.

The relationship seen in our experiments between the concentration of smoke in the tunnel and the density of diesel traffic also seems reasonable. Williams (1961) has shown that "the smoke concentrations from road traffic on busy roads can be appreciable and, for short periods, can produce intense local pollution". In Table 4 the tunnel results have been summarized and compared with outdoor concentrations of smoke and hydrocarbons. The lowest pollution encountered in the tunnel has been tabulated together with the mean values for other periods; the morning "rush hour" figures refer to samples taken between 07.00 and 10.00 hours on week-days, the evening "rush hour" to samples taken between 16.00 and 20.00 hours, and the daytime figures to those taken between 10.00

and 16.00 hours. The "holiday evening" samples were taken in the Blackwall Tunnel on a Sunday or Bank Holiday. The Central London figures provided for comparison are, with the exception of the carbon monoxide, based on results from a number of samples taken in the open air, away from traffic, at St. Bartholomew's Hospital. Typical summer and winter values are quoted together with the results from a sample taken during a period of high pollution on December 3, 1957; the smoke on that occasion came mainly from domestic chimneys and a low temperature inversion prevented it from dispersing normally.

During the quietest period in the middle of the night the concentrations of most pollutants in the tunnel fall to the same order of magnitude as those in the ordinary London air. At other times, when there is heavy traffic, the concentrations of all pollutants measured in this study are much higher than the typical summer or winter levels in outdoor air. The concentrations during the morning and evening rush hours are similar to one another, despite differences in traffic composition. The maximum concentration of smoke occurs in the daytime, when the number of diesel vehicles is highest. The concentrations of most of the hydrocarbons are also highest then, but coronene and 1 : 12-benzperylene, which appear to be associated rather more with petrol vehicles, show their highest concentrations during the rush hours. The concentration of carbon monoxide is highest on holiday evenings, when the number of petrol vehicles is at a maximum. The concentration of smoke and of most hydrocarbons is lower then than at any other busy time in the tunnel, although it is still many times the outdoor level.

Further comparisons within Table 4 show that all the concentrations of smoke and hydrocarbons in the tunnel are within the range found in ordinary London air. Those observed during busy periods can be regarded as similar to the concentrations of smoke and hydrocarbons found during temperature inversions on winter evenings in Central London. Carbon monoxide appears to be the only significant hazard; during the rush hours and on busy holiday evenings the concentration was generally over 100 p.p.m., which is the maximum allowed for continuous exposure in industry. Exposure to these concentrations for several hours may have perceptible effects and on several occasions during the course of these experiments the authors and their colleagues experienced headaches, fatigue, and general drowsiness after being exposed continuously for periods of three to 14 hours in the tunnel. Drivers are not normally exposed to these concentrations for more than 30 minutes in passing through the tunnel and no one else spends long there during the busy periods. Severe eye irritation was experienced at times, but the cause of this was not investigated. The oxides of nitrogen do not appear to present any special hazard. There is much more nitric oxide than nitrogen dioxide in the tunnel air. The concentration of the latter reached about 0.1 p.p.m. (Table 2), which is well below the 5 p.p.m. permitted in industrial atmospheres. The physiological effects of nitric oxide have not been studied widely, but it can combine with the blood in the same way as carbon monoxide. The effects of oxides of nitrogen have been discussed by Katz, Rennie, and Jegier (1959), who made measurements in a railway tunnel where diesel trains were operating; they considered that the concentrations of nitric oxide observed

there (of the order of 20 p.p.m. in instantaneous samples) were not sufficient to form detectable amounts of methaemoglobin in blood. There is at present no reason to believe that the concentrations recorded in the tunnel (up to 1.4 p.p.m. in continuous estimations, but higher in some spot samples) would produce any effect on man.

Conditions in the Blackwall Tunnel are expected to improve greatly when the twin tunnel now under construction comes into use. The existing tunnel will then be used for traffic in one direction only.

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