

Discussion.

The AUTHOR showed a number of slides illustrating the work described in the Paper, some of which were reproduced in *Figs. 11 to 14*. The Author.

In connection with the paving of the roadway, he would mention that the whole question of the paving had received a great deal of attention. Asphalt, granite setts and various other materials were considered, but, in view of the fact that the traffic ran almost in grooves, and hardly deviated more than a few inches to one side or the other, it was finally decided to adopt cast-iron setts. They had proved very successful, as skidding was almost non-existent, except when vehicles entered the tunnel while it was raining. However, he believed that a thoroughly satisfactory paving had been obtained, and he thought that it was one which was likely to give a very long life. It had taken on a certain amount of polish, but so far there was no wear to be seen.

As was no doubt inevitable in the case of a scheme which was spread over so many years, death had taken its toll of quite a number of those who had been associated with it. Sir Maurice Fitzmaurice, Past-President Inst. C.E., who had been associated with the preparation of the initial report, died before construction commenced. Half-way through the period of construction the death of Sir Archibald Salvidge occurred; it was due to Sir Archibald's initiative and driving-power that the scheme was initiated. Some 9 months before the tunnel was opened to traffic Mr. B. H. M. Hewett, M. Inst. C.E., the engineer in charge of the works, also died. His death was a very great loss to the Author's firm; Mr. Hewett was a man of great experience who had done invaluable work, and it seemed a tragedy that he should not have lived to have seen the conclusion of the great work on which he was engaged. Mr. Anderson felt that Mr. Hewett, rather than himself, should have presented the Paper to The Institution. In some ways it was impossible not to feel that Mr. Hewett's death was due to the tremendous amount of work that he had done. On behalf of Sir Basil Mott and the other members of his firm, Mr. Anderson wished to pay that tribute to Mr. Hewett's memory.

They also recognized that Mr. Hewett was not the only one who had given of his best in connection with the work, and he had been expressly asked by Sir Basil Mott to take the opportunity of thanking all those who had helped, advised and guided them, as well as all

The Author. those who had served them. Sir Basil Mott had particularly wished it to be emphasized that, although he was looked upon as the engineer, the undertaking was the result of team-work on the part of all concerned. On his behalf, Mr. Anderson had great pleasure in thanking everyone who had been associated with the undertaking.

Sir Charles Bressey. Sir CHARLES BRESSEY remarked that he had one qualification for taking part in the discussion, namely, that, acting on behalf of the Ministry of Transport, he had had various opportunities of seeing the operations in progress during the construction of the work. He was one of those who, like the Author, had walked along the bottom of the 44-foot tube, and he did not know of anything more impressive, except perhaps the sight he had had a year or two ago of the airship "Hindenburg" during construction; the airship had a much larger diameter than the tunnel, and in its great shed at Friedrichshafen seemed very nearly as impressive.

A great part of the Paper was devoted to the subject of ventilation, which was an indication of the extraordinary difficulty that that particular aspect of the work had presented. The cost was very high, but it was not altogether fair to take the figures at their face-value, owing to the enormous addition which had been made to the cost by the exigencies of local amenities. He hoped that there would not be many other tunnels built where the cost under that heading would be quite so high.

The traffic statistics given in the Paper were of particular interest, and were satisfactory, as the number of vehicles, which was over 3,000,000 per annum, was greatly in excess of the estimate. Although that number might seem a large one, it did not represent very dense traffic, and the tunnel was probably capable of carrying two or three times that flow. The promoters of the tunnel, if they had any misgivings on financial grounds, could look forward to better times when the traffic figures might be doubled or trebled.

The ventilation was very effective, and on frequent occasions the air in the tunnel appeared to be cleaner and fresher than the outside atmosphere. The particulars of the ventilation-system given in the Paper would be of great interest to those who were concerned with subsequent tunnels, and particularly, no doubt, with the tunnel which was shortly to be constructed under the Thames between Dartford and Purfleet.

Mr. Frank. Mr. T. PEIRSON FRANK felt sure that all present would wish to congratulate the Author and all those associated with him on the completion of such a splendid national undertaking. There had been a number of tunnel-projects recently; members of Mr. Frank's own staff had been engaged upon the preparation of reports on some of those projects, and they had been considering some improve-

ments in connection with the Thames tunnels. He imagined that *Mr. Frank*, the experience gained at Liverpool would prove helpful when some of the newer projects were translated into reality.

When the Mersey tunnel was first proposed, the intention was to finish the tunnel, both in Birkenhead and in Liverpool, at points before the present entrances were reached, and he presumed that the costs given in the first instance referred to the scheme as originally proposed; at any rate the actual costs showed a tunnel rather more than 900 yards longer than that originally placed before Parliament. He mentioned that fact because he had already described the work as a national one, and it would be seen that the contribution from the Ministry of Transport was £2,500,000; he submitted that that was not sufficient for a work such as the Mersey tunnel, and if the point he was making had never been put to the Ministry he hoped that it would be placed before them. He held a post in Liverpool at the time that the work was carried out, and he had been appalled at the prospect of all the traffic which would eventually use the tunnel being discharged at the point at which it had at first been proposed to discharge it. The cost of the necessary street-improvements would have been enormous, and, moreover, the traffic-difficulties would have been considerably increased. On those grounds he felt that there was good reason to ask for an increased grant towards the cost of the tunnel.

The figures on p. 515 of the Paper gave a daily average of 7,488 vehicles a day, excluding pedal-cycles. It was difficult to make any comparisons with the Mersey tunnel, but he wanted to make such comparisons as were possible; in the case of the Blackwall tunnel, which had a carriageway only 16 feet wide, during 12 hours of a day in the summer of 1935 when a census was taken, there were 7,712 motor- and horse-drawn vehicles. Cycles were not included in that census. The maximum speed in that tunnel was restricted to 8 miles per hour, which was not always attained on account of the horse-drawn vehicles. It would be clear, therefore, that in the case of the Mersey tunnel provision had been made for considerable expansion. He had no doubt that that expansion would come more rapidly than might be expected; in the case of the Blackwall and Rotherhithe tunnels, of which the carriageway in each case was 16 feet, the traffic had doubled within the last 7 or 8 years.

In the section of the Paper dealing with ventilation, he noticed that the maximum dilution had been taken as 2·5 parts of carbon monoxide per 10,000 parts of air. In the case of the smaller tunnels with which he was associated—they were each only $1\frac{1}{5}$ mile long—the endeavour was made to work to 2 parts per 10,000, but he did not

Mr. Frank.

say that that was always adhered to, on account of the increase in the traffic and the delays caused by horse-drawn vehicles.

If the tunnel were being constructed again, it would be of interest to know whether the Author would suggest adopting the twin tunnels referred to in connection with the Holland tunnel. He put that question on the ground of convenience in regard to ventilation, although he could see that there were disadvantages from the point of view of the traffic. It would be of interest to know how the section of rubber-surfaced roadway had been found to respond to the traffic through the tunnel. Presumably, the traffic was usually operated under what might be termed dry-weather conditions, and some of the difficulties in regard to skidding which had been recently discussed¹ might arise if the cast-iron road became wet.

With regard to the "run-in" described on p. 485, he happened to be on the top of it when the first explosion occurred, and he mentioned it because, whilst precautions were taken in connection with the water-mains, it was the gas-main which might have given rise to more serious trouble through the gas collecting in underground pipes or sewers. His staff had had to lay a sewer on the north side, under what was described in the Paper as the foundations of heavy buildings. They had tried to get the tunnel-authorities to do it, but had been unsuccessful and had had to carry out the work by direct labour.

He had had the opportunity of inspecting the work from time to time, and he much appreciated those opportunities. He had noticed that a small settlement was caused when the shield was at work. They had waited for a long time to renew the tramway-tracks in Dale street, which was over the tunnel, and in the end they had had to reconstruct them and to re-pave the street prior to the tunnel being driven under it. He then noticed a small settlement along the tram-rails, which extended for some time, but was relatively small. He thought that that might be avoided in future if somewhat similar ground had to be excavated by special attention being directed to the excavation near the crown of the shield. With regard to the cementation-process, he would like to know what pressures were originally instituted and what were used after some little headway had been made along the length of the tunnel.

He would like to add that not all the spoil was carried to waste; it had been possible to use a great deal of the excavated rock in the construction of a river-embankment some little distance from the

¹ R. G. C. Batson, G. Bird and R. E. Stradling, "Road Engineering Problems: Judging the Slippery Road," *Journal Inst. C.E.*, vol. 2 (1935-36), p. 443 (April, 1936).

site, where some 65 acres were ultimately to be reclaimed from the Mr. Frank. river.

Mr. G. G. LYNDÉ congratulated the Author on his Paper. The Mr. Lynde. Mersey tunnel presented a new problem, namely, that of magnitude. He referred principally to the river-section ; it was only the river-section where the full circle was used, and where that problem was presented in the most acute form ; that section of the tunnel was 1 mile from shaft to shaft, and was of such a size throughout that it would be possible to build inside it a three-storey house complete with foundations and chimneys. In the portion under the buried channel the top heading was lined with tube-iron, and the London tube looked relatively tiny compared with the tunnel. An interesting point which might be mentioned was that many geologists had long believed that in glacial times the Mersey flowed in the direction opposite to that in which it now flowed, and proof of that theory had been discovered.

The problem of magnitude was not only one of dealing with a large quantity of material in a small space, but was also one of the actual size of the tunnel itself. He had no hesitation in saying that the exceedingly wise decision, taken by the engineers, to construct the top part of the tunnel first was one of the most important decisions in the construction of the work. It enabled the bottom heading to be used for continuous traffic, and when there were five " break-ups " between the two shafts under the river, with ten faces working and almost continuous shot-firing, there would have been endless delays if the traffic had had to be taken through the " break-ups." As it was, the traffic went on uninterruptedly in the bottom heading while the arch was being constructed. Another important decision was the construction of the suspended roadway, which carried three lines of traffic. Over that suspended roadway, traffic passed continuously day and night while the invert was being constructed. The excavation under the river amounted to about 4,000 tons a week, and rose to a peak of 7,000 tons per week ; the Liverpool shaft, which dealt not only with the river but with part of the Liverpool approach, had a peak of 7,000 tons a week, which meant one wagon per minute lifted 130 feet from the bottom of the shaft to the tipping-stage. That was done by a series of high-speed lifts, which proved very satisfactory for their purpose. The arch had been built, and the invert had been put in, without any trouble, and, looking at the finished tunnel, it seemed as if there had been no difficulties during the construction. A great deal of anxious thought had, however, been necessary before the various decisions had been reached.

He would like to refer to the construction of the junction-chamber

Mr. Lynde. under Dale street; it was a large chamber 66 feet long with an arch-span of 51 feet. It was entirely constructed in tunnel, and 7,600 cubic yards of excavation were taken out of it. It was constructed by driving headings 6 feet wide and 25 feet high, all round the four sides, and those headings were filled with concrete and became the walls. Headings 4 feet wide were then driven across in which steel ribs were placed and concreted up, so that the arch was gradually formed; the dumphing was then removed.

He would like to mention the excellent work done by the late Robert Guthrie and the late Frederick Budden, successive walking gangers, and by the night-walking ganger, William Lawrence. He would also like to draw attention to the fine qualities of the men employed on the work; their resourcefulness was demonstrated in the case of the "run-in" mentioned on p. 485, where their prompt and plucky action prevented what might have been a very serious mishap. The men who drove the drainage-channel also deserved mention. Very little had been said about that channel, which was driven 1,500 feet out under the river at a depth of 170 feet below high water; it was 7 feet in diameter and produced 4,000 gallons of water a minute. Those men worked under appalling conditions, but they did their job well.

He could add little to what the Author had said regarding Mr. Hewett, who had brought to the work great experience and wisdom. The success with which the work was carried out owed much to the regular meetings between engineers and contractors at which the various difficulties were freely and fairly discussed. The leader in all that team work had been Sir Basil Mott.

Mr. Colquhoun. Mr. C. B. H. COLQUHOUN remarked that an interesting comparison could be made between the Mersey tunnel and two other tunnels of the same type which had recently been built, namely, the Holland tunnel in the United States, and the Antwerp tunnel. The outside diameter of the Mersey tunnel was just over 46 feet, that of each of the two Holland tunnels being $29\frac{1}{2}$ feet and that of the Antwerp tunnel being a little over 30 feet. The total number of track-feet (namely, the length of the tunnel in feet multiplied by the number of tracks) was 53,000 in the case of the Mersey tunnel, 37,000 in the case of the Holland tunnel, and 13,850 in the case of the Antwerp tunnel; that gave some idea of how much larger the Mersey tunnel was than any other tunnel of the same type. The Holland tunnel was opened in 1927 and the Antwerp tunnel in 1933, and comparative figures were set out in Table II. It did not appear, from the figures of cost per track-foot, that the total cost of the Mersey tunnel was really so very great. The increased volume of the ventilation-buildings for the Mersey tunnel was due to the

greater length of the tunnel, together with the provision of 100 per cent. stand-by plant, instead of only 50 per cent. stand-by plant as in the case of the other two tunnels. The size of the Mersey tunnel as compared with the other tunnels would be realized when Table II was studied.

TABLE II.—A COMPARISON OF SOME OF THE CHARACTERISTICS OF THE MERSEY, HOLLAND AND ANTWERP TUNNELS.

Characteristic.	Tunnel.		
	Mersey.	Holland.	Antwerp.
Length from street to street : feet . . .	15,191	9,200	6,924
Track-feet, surface to surface . . .	53,000	37,000	13,850
Outside diameter : feet . . .	46.25	29.5	30.83
Cross-sectional area : square feet . . .	1,680	682	744
Volume of tunnel-excavation : cubic yards . . .	684,000	475,000	203,000
Maximum depth below water : feet . . .	160	110	120
Cost of works, excluding land and fees : £ . . .	5,920,000	7,427,000	1,800,000
Cost of works per track-foot : £ . . .	111	200	130
Cost of works per cubic yard of excavation : £ . . .	8.65	15.60	8.86
Cost of land, excluding fees : £ . . .	878,000	1,460,000	160,000
Cost of land per track-foot : £ . . .	16	40	12
Total cost, works and land (no fees) : £ . . .	6,798,000	10,350,000	1,960,000
Total cost per track-foot : £ . . .	127	277	142
Cost of ventilation-buildings : £ . . .	510,000	750,000	128,000
Cost of ventilation-buildings per track-foot : £ . . .	9.6	20	9
Cost of ventilating plant : £ . . .	242,000	373,000	80,000
Cost of ventilating plant per track-foot : £ . . .	5	10	6
Total volume of air, fresh and exhaust : cubic feet per minute . . .	10,000,000	11,521,000	2,000,000
Volume of air per track-foot : cubic feet per minute . . .	190	311	144
Number of ventilation buildings . . .	6	4	2
Track-feet of tunnel per ventilation-building . . .	8,166	8,368	5,800
Total volume of ventilation-buildings : cubic feet . . .	4,418,000	2,992,000	621,000
Volume of ventilation per track-foot : cubic feet . . .	85	82	45
Cost of ventilation-buildings per cubic foot of building . . .	2s. 3d.	5s.	4s. 1½d.
Proportion of stand-by ventilation plant : per cent.	100	50	50
Maximum distance between ventilation-buildings : feet	4,510	3,375	2,798

The operation of the tunnel was carried out in a way which he thought was rather unusual. It had originally been expected that

Mr. Colquhoun. the Joint Committee, the statutory body responsible for the tunnel, would employ a complete staff of its own, but that scheme was eventually superseded by one in which the operation of the tunnel was carried out by what was called the "contracting-out" system. The work of operation was divided into a number of parts, such as ventilation, cleaning, and toll-collection, and each of those sections of the work was let out by tender to the Corporations of Liverpool and Birkenhead, the lower of the two tenders being accepted. That seemed a curious method of operating the tunnel, and he would not care to say that it was the most economical or the most efficient. There were one hundred and seventy-seven permanent and about forty-five part-time employees, the latter being accountants, clerks, or other staff of the Corporations, who were employed part-time on the tunnel. Assuming that the part-time employees gave half their time to the tunnel, that inferred an additional twenty-two employees, or a total operating staff of practically two hundred. That might seem a very large staff, but in view of the amount of traffic going through he did not consider that it was really too great.

In the first year, as stated in the Paper, over 3,000,000 vehicles (including pedal-cycles) used the tunnel. The actual number of motor-propelled vehicles was 2,672,000, and that was divided up into approximately $33\frac{1}{2}$ per cent. of commercial vehicles and $66\frac{1}{2}$ per cent. of private vehicles. There had so far been an increase during the second year, which was not yet complete, but, comparing two representative months, September and October, 1934, of the first year, with September and October, 1935, the number of vehicles during September, 1934, was 243,000 and for September, 1935, it was 268,000. In October, 1934, and in the same month of 1935, the figures were 195,000 and 238,000 respectively. The decrease from September was purely due to the normal fall in traffic during the winter. The increase was 10.3 per cent. for September and 22.0 for October, the average over the two months being 16 per cent. Apparently there would be an annual increase in traffic of about 14 to 16 per cent.

It was of some interest to investigate those figures. The Birkenhead ferries carried, before the opening of the tunnel, about $1\frac{1}{4}$ million motor-propelled vehicles, of which about 64 per cent. were commercial vehicles and 36 per cent. private vehicles. In the case of the tunnel the proportions had undergone a great change. Commercial vehicles formed 64 per cent. of those using the ferries, but only $33\frac{1}{2}$ per cent. of those using the tunnel. On going into the figures a little more closely, it was found that the actual increase in commercial vehicles using the tunnel in the first year as compared with those using the ferries the year before was only 12 per cent.

In other words, it was the same as the annual increase which had occurred in the first two years of the use of the tunnel, so that probably the same number of commercial vehicles would have used the ferries had the tunnel not been open. The great increase had, however, occurred in the private vehicles. Whereas on the ferries their percentage was 36, in the tunnel it was 66½, and the actual increase in the number of private vehicles using the tunnel in the first year was 295 per cent. In spite, therefore, of the fact that the tunnel was primarily built for commercial traffic, it seemed that it was the private traffic which was ultimately going to pay for it.

The results of the efficiency-tests and experiments which had been carried out on the ventilation-plant showed that a great deal of the horse-power involved in running the plant was used up in overcoming the friction of various bends and awkward places in the ducts. That was a point which would, he thought, have to be given even greater consideration in any future tunnel than it had been in the case of the Mersey tunnel. Most of the fans which were used were of the old centrifugal type which had been in use for the last hundred years, but at Woodside, where the buildings were not completed when the tunnel was opened, there were two axial-flow or propeller-type fans installed temporarily. Such fans had originally been considered for use in the tunnel, but they were taken out for various reasons, among which were lack of experience with them, and insufficient time for prolonged reliability-tests, as well as poor efficiency-figures and excessive noise. The experience with those propeller-type fans at Woodside, however, was that they had been running for from 16 to 18 months night and day without a stop, and he thought that that was sufficient to show their reliability. A considerable amount of research-work had been carried out which had overcome their disadvantages, and he thought that the propeller-type fan had now reached a stage when very serious consideration would have to be given to it for future work in tunnels. Its use would have other advantages, in that it would simplify the design of ducts and would reduce the resistance, enabling less horse-power to be used; in general, he thought that, in future, ventilation-buildings and plant would be much smaller and simpler than in the case of the equipment for the Mersey tunnel.

The two assumptions on which the amount of ventilation had been based were, firstly, the amount of carbon monoxide emitted by a vehicle, and secondly the amount of carbon monoxide which could be permitted to be in the atmosphere of the tunnel at any time. The first figure was deduced primarily from experiments which had been carried out by the United States Bureau of Mines for the Holland tunnel; the results of those experiments gave a figure of 1½ cubic

Mr. Colquhoun. foot of carbon monoxide per vehicle per minute. The amount of carbon monoxide which could be permitted in the tunnel atmosphere was laid down by the late Professor J. S. Haldane. Since the tunnel had been opened, there had been an opportunity of determining those figures more accurately, and it had been found that, instead of taking 100 cubic feet per hour, it was only necessary to provide for from 55 to 60 cubic feet of carbon monoxide per vehicle per hour. That was probably due to the greater efficiency of the internal-combustion engines used in motor-vehicles in Great Britain.

Mr. Brown. Mr. R. D. BROWN remarked that 26 years ago he had come to the end of a 7-year period in tunnelling operations, and since then he had not been greatly interested in tunnel-work. During the last few years, however, he had been asked by the late Mr. H. A. Reed to investigate certain aspects of tunnels under the Humber and under the Thames at Dartford, and he had found it surprising that, after such a long interval, the same methods were still in use, particularly in regard to the cast-iron lining and the cross-sectional shape of the tunnel.

It was 69 years since Barlow first used a cast-iron lining in a small tunnel which he was driving under the Thames, and, with a few exceptions, a cast-iron lining was still adhered to in Great Britain. In the case of small tunnels it had great advantages in weight and permanence, but as compared with steel it was a weak and brittle material, and when the segments were filled with concrete the deep flanges of the iron separated the concrete into small pockets which were of no value from the point of view of strength, but merely added dead weight. In the case of a tunnel of the magnitude of that under the Mersey, Mr. Brown thought that it would be worth while to consider steel as an alternative for the lining. A thin skin could be used to keep the water out during the setting of the concrete, but inside that skin there would be very strong open-work structural-steel ribs, with steel reinforcing rods through the concrete both longitudinally and circumferentially, which would give much greater strength and at the same time a greatly reduced cost. The main structure of the lining would be embedded in concrete and would have a great deal more permanence than cast iron, even if the thin outer skin rusted away in course of time.

A beginning had been made on the Continent and in the United States with the use of steel lining for tunnels. The earliest reference to it which he had been able to find was in 1930.¹ The first use of

¹ "The Detroit-Windsor Tunnel," *Engineering*, vol. cxxx (1930), pp. 605, 667, 702.

steel in the U.S.A. was experimental and was not altogether a success, Mr. Brown, because it was a shield-driven tunnel and the jacks crumpled the longitudinal member, but those difficulties had been overcome, and it was now found that, from the point of view of cost, steel had important advantages. He had made a very rough estimate on the basis of costs ruling in 1930 for a 48-foot diameter tunnel, and on a most conservative basis he thought a sum of £275,000 might have been saved in the construction of the Mersey tunnel had steel been used.

With regard to shape, and particularly in the case of large air-driven tunnels, it seemed to him a great pity to adhere to the circular form, as was nearly always done in Great Britain. He had prepared a memorandum on those lines and had circulated it in 1931 to a number of engineers and contractors, including the engineers of the proposed Dartford tunnel; he had been very pleased to see in the public press recently that the large vertical diameter formerly proposed for the Dartford tunnel had now been reduced, which would permit a great relief in the air-pressure and would considerably improve the lack of balance between the air pressures at the crown and the invert. If that tunnel were driven under compressed air, he thought that, owing to its great depth in fissured chalk, it would prove one of the most difficult works ever undertaken in Great Britain. There were other methods of construction which would be safer and less costly.

Cracks had occurred in the lining of a certain tunnel many years ago, and had caused great consternation amongst all concerned. Calculations based on certain assumed data were then made and were taken to Sir Benjamin Baker, Past-President Inst. C.E. When Sir Benjamin looked at them, he said, "It would be quicker to assume the thickness than to assume the data." He added that the thickness for the 26-foot diameter Blackwall tunnel was "assumed" at 2 inches under the river and $1\frac{1}{2}$ inches under the land.¹ Perhaps the Author would amplify his valuable Paper by giving some of the reasons which led to the adoption of a skin-thickness of $1\frac{1}{2}$ inch in the case of the Mersey tunnel.

MR. J. L. HODGSON associated himself with previous speakers Mr. Hodgson, in complimenting the Author and his firm on the very great engineering achievement which they had carried out so successfully.

Apart from his work on air-measurement in connection with the ventilation of the tunnel,² there were two points to which he desired to refer. The first dealt with the glacial channel which Professor

¹ Minutes of Proceedings Inst. C.E., vol. clxxxi (1909-10, Part III) p. 227.

² Mr. Hodgson's remarks on that subject will be published in the Correspondence on the Paper.—SEC. INST. C.E.

Mr. Hodgson. P. G. H. Boswell, from his great knowledge of the local effects of glaciation, had been able to say ran in the opposite direction to the river along the present course of the Mersey. Professor Boswell had thus been able to save the Tunnel Committee many thousands of pounds. The channel had been found when the Mersey Railway tunnel was driven in 1884, and it had been assumed that it would be deeper at the site of the road-tunnel, which was situated nearer the sea. Professor Boswell, however, was able to show that it would be a certain amount higher.

In connection with the general subject of glaciation, Mr. Hodgson desired to draw attention to a book by Mr. H. E. Forrest,¹ a field naturalist, in which was correlated an immense amount of biological and geological data. Mr. Forrest, in an attempt to explain why certain forms of plant and animal life were common rather to Ireland and North America than to Ireland and England, had been led to study the ice-markings and glacial deposits, as well as the contours and composition of the ocean-bed throughout the North Atlantic area. That study had led Mr. Forrest to the conclusion that, in Pleistocene times (about 1,000,000 years ago), much of the bed of the Atlantic, including Iceland, had been some 12,000 feet higher than at present, and that that high land had given rise to an ice-sheet. That ice-sheet, emanating from Iceland (then about 17,000 feet high), had had sufficient pressure behind it, with a mean gradient of about 17 feet per mile, to force its way over the mountains of Ireland and the Isle of Man, as far as the Shannon and Thames valleys. Whether the particular deductions of Mr. Forrest were correct or not, the whole question of glaciation was one which should be of great interest to members of The Institution, as the ice-sheet, when it melted (from 30,000 to 10,000 years ago), deposited gravels, sands and clays, and eroded channels, which almost everywhere in Great Britain affected the work of the civil engineer.

The other point to which Mr. Hodgson wished to refer dealt with the financing of the tunnel. As was usual in such cases the interest and sinking fund amounted to three times the money loaned to enable the tunnel to be built by the engineers, $3\frac{3}{4}$ per cent. per annum having to be paid for a period of 80 years.

Mr. Hodgson then showed a cinematograph film of the construction of the tunnel.

He then quoted the following words which His late Majesty King George V used at the opening ceremony, and which set the seal of Royal approval upon such activities as tunnel-making :—

“ . . . a thoroughfare so great and strange as this new Mersey tunnel now made ready by your labour.

¹ “The Atlantean Continent” (Second Edition), London, 1935.

“Who can reflect without awe, that the will and power of Mr. Hodgson. man can drive tunnels such as this, wherein many streams of traffic may run in light and safety beneath the depth and turbulence of a tidal river bearing the ships of the world?”

“May those who use it ever keep grateful thought of the many who struggled through long months against mud and darkness to bring it into being.

“I praise the imaginations that foresaw, the minds that planned, the skill that fashioned, the will that drove, and the strong arms that endured. . . .

“Such a task could only be achieved by the endeavours of a multitude.

“May our peoples always work together thus for the blessing of this kingdom by the wise and noble use of the power that Man has won from Nature.

“I thank all those whose efforts have achieved this miracle.”

DR. W. L. LOWE-BROWN congratulated the Author on his Paper. Dr. Lowe-Brown. The truly national character of the Mersey tunnel was recognized by His late Majesty King George V, who opened it, and by Her Majesty Queen Mary, who allowed it to be called Queensway.

The late Mr. Hewett, the Engineer-in-Charge, had been one of Dr. Lowe-Brown's most intimate friends. Dr. Lowe-Brown had had many opportunities of visiting the tunnel with Mr. Hewett, so that he was familiar with most of the work described in the Paper. Further, Sir Basil Mott had given him the opportunity of being directly connected with the work, as when certain modifications of the design of the cast-iron lining were under discussion, Sir Basil had asked him to make the calculations for the modified design.

The Author was to be congratulated on having covered so much ground in the length of an ordinary Paper, but Dr. Lowe-Brown felt sure that the Author would be the first to acknowledge that he had had to omit a great many particulars. He would like, therefore, to suggest that the Author might allow members of his staff, or others connected with the work, to write a series of Papers putting on record all the important details which would be of use to other engineers.

In the short section of the Paper devoted to the history of the project there was nothing with regard to what was nowadays called “planning.” The reasons why a 4-track tunnel was adopted instead of two 2-track tunnels might be known to many, but Dr. Lowe-Brown would suggest that some reference should be made to them by the Author. Another subject which had been referred to, and which had been touched upon by the Author, was geology. Before

Dr. Lowe-
Brown.

the headings were driven, Professor Boswell had forecast the nature of the rock which would be passed through and the position of the faults which would be met, and that forecast was found to be very accurate. During the construction, much additional information was obtained with regard to the Upper and Middle Bunter Sandstone beds, such as the amount and level of water contained in them, the differences of water-level across the faults, and the effect of the construction of the Mersey tunnel on the pumping in the Mersey railway tunnel. There were many questions connected with the construction, such as excavation-methods, cementation-methods, caulking experiments and difficulties of grummeting about which information might with advantage be given by the Author. Some account of the numerous kinds of interior finish that were investigated, and the reasons for the adoption of the type described in the Paper, would also be of interest.

The most important question of all was probably that of ventilation. Extensive researches had been made on the various systems of ventilation, and some particulars would be most useful. The Americans had published a considerable amount of detailed information on the results of their experiments, particulars of which must have been most helpful to the engineers of the Mersey tunnel as a starting point for their researches. In the section headed "Ventilation" the Author stated: "The maximum dilution has been taken to be 2.5 parts of carbon monoxide per 10,000 parts of air at times of peak traffic; under ordinary conditions it will be well below this figure." In the American tunnels, the maximum amount of carbon monoxide permissible was 4 parts per 10,000 in times of peak traffic, but the actual amount of pollution never reached that figure. Further, in a pamphlet¹ previously published by the Mersey Tunnel Joint Committee it was stated that 2.5 parts per 10,000 would be the maximum pollution under ordinary conditions, but that this might be increased to 4 parts in times of extreme peak load. Perhaps the Author would make that point quite clear, because, if it had been found necessary to adopt a much higher standard of purity in England than in America, it would be interesting to have some attention drawn to that fact.

Reference had already been made to the streamlining of the air-ducts and the losses in the bends, but he felt sure that further information was available; he asked the Author to allow it to be made public. Mr. Colquhoun had already referred to the question of cost, so that it was unnecessary to say more on that point, beyond

¹ "The Story of the Mersey Tunnel, officially named Queensway," London, 1934.

the fact that the Mersey tunnel had been built very cheaply compared with most other tunnels. Dr. Lowe-Brown.

MR. N. G. GEDYE associated himself with previous speakers in congratulating the Author and his colleagues on the magnificent work which they had carried out. In 1931 he visited and investigated in some detail the construction and operation of two of the subaqueous vehicular tunnels in the United States, namely, the Holland tunnel under the river Hudson, and the tunnel beneath the Detroit river between Windsor (Canada) and the United States. The Author stated, in the section headed "Ventilation" (p. 492), that in the Holland tunnels there was a longitudinal movement of air induced by the passage of traffic in one direction, but Mr. Gedye's experience was that there was practically no longitudinal air-current in the Holland tunnels or in the Detroit-Windsor tunnel. On several occasions he tested the matter when standing on the sidewalk of the tunnel, by blowing volumes of cigarette-smoke into the air; the smoke ascended almost vertically to the air-grids in the ceiling immediately overhead. Even on a Sunday in August, 1931, when 2,227 vehicles came into New York through the south tunnel between midnight and 1 a.m., he noticed that there was hardly any longitudinal air-current, as the cigarette-smoke ascended with only a very slight inclination towards the direction of the traffic. In the Holland tunnels, even at times of maximum density of traffic, the carbon-monoxide content rarely exceeded 2 parts per 10,000, and a complete change of air in the tunnel took place forty-two times in 1 hour, or once in about $1\frac{1}{2}$ minute. He had checked that figure by examining the carbon-monoxide records for a considerable period, and had taken particular note of the results for Sunday nights, when the traffic was most intense, but he had found no record as high as 2 parts per 10,000. He was told that there had been one or two records slightly in excess of 2, but those were far short of 2.5, although the ventilation-arrangements were designed on the basis of 4 parts per 10,000. It should be noted that all the American vehicular subaqueous tunnels, as well as the Antwerp tunnel, were ventilated on the upward transverse system. Mr. Gedye.

It might be of interest to record a few facts about those tunnels and also about other American vehicular tunnels, particularly in regard to the differences between them and the Mersey tunnel. The traffic in the Holland tunnels in the year 1931 amounted to 12,756,174 vehicles, as compared with 3,063,923 in the Mersey tunnel during its first year. On one Sunday in 1931, 59,000 vehicles passed through the Holland tunnels in 24 hours, and the maximum traffic in one tunnel for one hour in one direction only had been over 2,500 vehicles. The traffic figures on Sundays normally exceeded

Mr. Gedye.

50,000, and on the particular day on which he spent some hours there, he believed the figure was 52,000. The official estimate of the maximum traffic-capacity of the Mersey tunnel was, he believed, 4,150 vehicles per hour with four lines of cars spaced 100 feet apart and moving at 20 miles per hour. It did not seem possible, however, that such a figure could be realized in practice in the Mersey tunnel, even supposing that the in-going and out-going streams were equal in volume, because of the inevitable check caused by the crossing of traffic lines at the junctions of the branch tunnels with the main tunnel in Liverpool and Birkenhead. It seemed to him that the arrangement of the branch-tunnel traffic crossing the main-line traffic in the Mersey tunnel was in many ways an undesirable feature, and must result in considerably reducing the traffic-capacity of the main 4-way tunnel, unless at times of intense traffic the branches were temporarily closed; in that case it would be possible to get nearly 4,000 vehicles passing through the main tunnel alone if the north- and south-going streams were approximately equal in volume.

All the subaqueous vehicular tunnels at present in operation in the United States, with the exception of the Holland tunnels, were single tunnels providing for two lines of traffic in opposite directions. In the Detroit tunnel, in spite of international customs and passport regulations at both ends, a traffic of more than 2,000 vehicles per hour on two lines of traffic in a single tube was reached even in the period of intense industrial depression which followed its opening in 1930. The maximum daily intensity of traffic up to 1931 was 10,800 vehicles, but that figure was much below the maximum capacity. In the Oakland tunnel, under an arm of San Francisco Bay, the number of vehicles passing through the single two-way tunnel had exceeded 1,800 in each direction per hour; that was, 3,600 for both directions. The Sunday and holiday traffic varied from 22,000 to 27,000 vehicles, and the weekday traffic from 18,000 to 20,000 vehicles, per day. The tunnel under Boston harbour was also a single two-way tunnel.

It need not be assumed that the difficulty of clearing traffic-blocks due to accidents was greater in a small two-way tunnel than in a four-way tunnel such as that under the Mersey. He had witnessed a collision in the Holland south tunnel on the Sunday night in summer to which he had already referred, the particulars being noted by the Chief of Police, who was with him, and himself. They happened to be standing on the footway close to the site of the occurrence. The east-going traffic at that moment—he looked at the record afterwards as a check—was at the rate of about 2,500 vehicles per hour in the one tunnel. Two cars, going in the same direction, became locked. The traffic was at once cleared in advance of the

locked cars, and was resumed in one lane in 2 minutes after the Mr. Gedye. accident. The breakdown-car came into the tunnel, but it was not required, as the cars were separated in 3 minutes from zero time and were able to proceed under their own power, although both were damaged. Traffic in both lanes was proceeding normally in under 4 minutes from the time of the impact.

There was another point of difference to which he might draw attention. The cross-sectional area of the Mersey 4-way tunnel was 1,680 square feet, while that of each of the 29½-foot diameter Holland tunnels was 683·4 square feet. It seemed to him that if a single 2-way tunnel had been constructed under the Mersey in the first instance, it might have been available for traffic several years before the present tunnel was available, and would have been amply sufficient for all the traffic which at present used the tunnel. The tunnel might have been duplicated if and when the growth of traffic justified such duplication. An enormous saving in initial cost would have been made and a consequent saving on interest and amortization charges for a good many years. The cost of two 2-way tunnels under the Mersey would, he suggested, have been less than the cost incurred in building the Mersey tunnel in its present form, and incidentally the traffic difficulty to which he had referred would have been obviated in that way. The so-called "Mid-Town" tunnels, which represented the most recent American practice, and the first of which was now being driven under the Hudson higher up the river than the Holland tunnels, would be twin tunnels, each 31 feet in external diameter. In the first instance the south tunnel, which it was expected to open for traffic early in 1938, would be utilized for two-way traffic with one line in each direction, as in all the other American tunnels except the Holland. At some later date, when the growth of traffic justified its construction, the second tunnel would be built, and, when both tunnels were in operation, one would be used for two lines of east-going traffic and the other for two lines of west-going traffic, as in the Holland tunnels.

In the ventilation-plant of the Holland tunnels, the motors and fans were of much smaller individual capacity than those in the Mersey plant, but there were eighty-four fans in all, as compared with thirty in the Liverpool and Birkenhead buildings. One-third of those fans comprised a reserve of 50 per cent. over the normal maximum output of 3,760,000 cubic feet of fresh air per minute, which was the capacity of the blowers alone, excluding the reserves. All the fans were driven by 5-speed motors, and at times when the traffic was relatively light, one set of two fans, one blowing and one exhausting, in each of the fourteen ventilating-sections, sufficed to maintain sufficient ventilation when run at the lowest speed. It

Mr. Gedye.

had been established that samples of air taken in the open near the junction of 42nd Street and 5th Avenue in New York frequently contained a higher proportion of carbon monoxide than was ever met with in the tunnel. His own view was that upward transverse ventilation, as in the American tunnels, was the system to be preferred in tunnels of relatively small diameter carrying two lines of traffic, although there were probably distinct advantages attaching to the semi-transverse system in the case of tunnels of very large diameter, such as that under the Mersey.

The paving used in all the American tunnels was granite setts. In the Holland tunnels the setts were in straight lines transversely. The granite paving in the Detroit-Windsor tunnel was, however, laid in courses of circular arcs and the joints were run in with hot bitumen and sand. The surface was said to be very satisfactory and much better than that of the Holland tunnels. It was claimed that skidding had been practically eliminated by the paving in the Detroit tunnel, and he believed that a similar paving had been used in the Boston tunnel.

Mr. Kennedy.

Mr. J. J. S. KENNEDY said that the Paper was of especial interest to him, as it described much of which he had been ignorant during his connection with the Mersey tunnel, which dated from January, 1931. He would like to ask one or two questions on matters other than the actual construction and structure of the tunnel. Would the Author tell him the air-velocity in the north and south air-ducts? He would also like to know the velocity along the south air-duct half-way from the Liverpool bank to the neutral point where the Liverpool air met the Birkenhead air. It had been stated in 1931 that the velocity would be about 40 miles per hour, and there was some alarm at the prospect of having to make high-voltage cable-joints in such a high horizontal wind. In the section on ventilation the Author stated that the inlet-velocity to any section was never less than 15 feet per second with the full quantity of air passing. That gave a speed of about 10 miles per hour, but in *Figs. 9*, the curve showed a maximum flow near the entry equivalent to about 19 miles per hour.

In the section of the Paper headed "Control-Room" (p. 507), the Author mentioned the diminution of visibility owing to smoke and fog. Visibility might be diminished by either solids in the air, smoke-dust or dirty fog, which obstructed actinic light, or by clean condensed water-vapour, such as mist, which merely diffused the light. The problem was analogous to that of working the lighting of aerodromes automatically by the diminution of visibility when there had been no diminution of actual light. He would like to ask whether, so far, any clean mist had been experienced in the Mersey tunnel,

whether the light-sensitive cell functioned equally well with clean Mr. Kennedy. mist, and whether it was intended to make the photo-electric cell not only indicate the visibility but also actuate the tunnel lighting. It was satisfactory to learn that light-sensitive apparatus was being used for vehicle-counting and for vehicle-height limitation.

He would also like to know why air-flow recorders of the impact-plate type were being used, and whether consistent and true readings were possible with such recorders. In the section on ventilation the Pitot-tube type was stated to have given the only reliable results, and that confirmed his own experience in aviation work and in large power-station flues and chimneys, which was that a small Pitot head, with its static and dynamic orifices connected by its concentric tube to a manometer, was the only reliable means of finding the velocity and direction of air-movement. He had found that no flat plate with sharp edges could give true results, as it involved turbulence and itself interfered with the air-flow. He had watched a recorder of that type in the main air-duct under George's Dock the previous summer.

The Mersey tunnel was thought of primarily as a road-traffic route between Liverpool and Birkenhead, but it was also the main power-connection route between those two cities, with a carrying-capacity of 40,000 kilovolt-amperes at a potential of 33,000 volts. The cable-run presented unusual features, of which there had been no previous experience. He had been responsible for the design of that cable-run, for the preliminary prospecting, for the specification and contract, and for the supervision during construction. It was soon recognized that the cable-run involved major engineering operations and problems. Although the cable-contract was not made until July, 1932, prospecting visits had had to be made during the latter part of the construction of the tunnel in 1931, before the rock excavation was finished or any of the roadway made.

The cable-run in the tunnel was briefly as follows. It ran down from Brunswick street (Figs. 1, Plate 1) at George's Dock, through a hole which was bored through one of the arches of a viaduct, through a cable-subway 6 feet by 6 feet by 70 feet in reinforced concrete which had to be made under the future tunnel-workshops, and down to the tunnel by a vertical shaft and passages. It continued (Figs. 1, Plate 1) through the circular part of the tunnel under the Mersey by the south air-duct, and then up Morpeth Dock working-shaft to become again ordinary underground cable in Shore road, Birkenhead. The cable-cores were each of 0.25 square inch in area, the cable used being of the 33-kilovolt 3-core Hochstadter sheathed-lead type, bare-wire-armoured and waterproofed where it lay in the ground. It weighed 56.1 pounds

Mr. Kennedy. per yard, and had an outside diameter of 3.88 inches with a minimum bending radius of 6 feet. Three of those power-cables, together with one pilot-cable, had been run through the tunnel, and space had been arranged throughout, with ducts and hook-racks, to accommodate another three cables and pilot-cable, making a total future capacity of approximately 80,000 kilovolt-amperes.

Some points in the design of the run which had had to be dealt with might be mentioned. The joints in the south air-duct had to be of special design and staggered in order to avoid any obstruction to the air-flow. On vertical runs the cables were gripped by teak grips 2 feet in length spaced vertically 10 feet apart. Information from South Africa and elsewhere was obtained, so as to avoid risk of too high a clamping-pressure damaging the cable, or of too low a pressure allowing it to slip. Previous experience was not available to deal with the gradients involved by the cable-run or with a vertical 33-kilovolt cable, and the problem of oil-migration at the joints had to be considered. The arrangement of the different types of joints was that there were two barrier reservoir-joints at the top and bottom of each vertical run, and one ordinary barrier joint along the tunnel at a lower position. High-voltage cables for 33,000 volts had to be handled carefully, and the difficulty of getting them into place in the run through the tunnel would be appreciated.

Mr. Lister. Mr. J. E. LISTER, after congratulating the Author on an excellent Paper, remarked that he had been directly concerned only with the ventilation-problem, but had spent a great deal of time in the tunnel during the whole of the construction period. The Author had referred to Mr. Lister's visit to the United States with the late Mr. Hewett. He had been very pleased to have the opportunity of making that visit and of seeing what had been done there in the ventilation of vehicular tunnels. At that time there were only two such tunnels actually in use, the Holland tunnels and the Pittsburg Liberty tunnels, but Mr. Hewett and himself had also seen the Detroit-Windsor tunnel, which was then under construction. Unfortunately, time had not permitted them to go to San Francisco to see the Oakland tunnel. He would like to express his thanks, as he was sure Mr. Hewett would have wished to have done, to Mr. Singstad and the other American engineers, who went to a great deal of trouble to see that the visitors had every opportunity of inspecting both the work in and on the tunnels and also the ventilation-buildings.

As the Author had mentioned, the New York and Pittsburg tunnels, which were the only ones then open, were designed for single-way traffic, and the problem of ventilation was quite different from that in the Mersey tunnel, with its larger area and branch tunnels. As a previous speaker had remarked, owing to that fact

the individual fans used in America were very much smaller than Mr. Lister. any which had been installed for the Mersey tunnel. As the Author was aware, he had particularly noticed the use of two fans in parallel for the peak loads, and he had advocated that, and would still advocate it, for any medium-sized installations. In the case of the Mersey tunnel, however, a single fan dealt with the whole of the air in each section, except in the case of the fresh-air fans at Woodside, where constructional difficulties had made it necessary to run separate supply shafts down each side of the tunnel.

Owing to those features, the largest fresh-air fans in the Holland tunnel—the conditions in which were somewhat comparable with those of the Mersey tunnel although, as Mr. Gedye had pointed out, it handled a great deal more traffic at present than the Mersey tunnel—were designed for a volume of 218,000 cubic feet per minute, as against 496,000 cubic feet per minute in the case of the George's Dock fans. The largest exhaust-fans in New York were designed to handle only 227,000 cubic feet per minute, as against the 641,000 cubic feet per minute of the exhaust-fans at Woodside.

The Author had mentioned the difficulty of estimating exactly what the resistance of the various sections of the ventilation-system would be. Although there was nothing strictly comparable with the conditions at Liverpool (owing to the larger size of the Mersey tunnel and to the different dimensions of the ducts, as well as to the presence in them of columns supporting the roadway), he had studied all the information available from various sources at that time; he had arrived at certain figures for what he thought was likely to be the resistance of the various sections of the tunnel, and had allowed a small margin for safety. Owing, however, to the care with which the surfaces of the ducts were finished and to the streamlining of obstructions, and in spite of the cables put in by the previous speaker, the actual resistance was, in most cases, appreciably less than the estimated figures, and consequently the actual volumes delivered by the various fans when running at full speed were greater than the figures originally calculated. He agreed with the Author as to the inapplicability of the Singstad formula to the conditions of the Mersey tunnel, but it did give a fair indication of the approximate values of the resistances of the various ducts before a sufficient length of the tunnel was completed to allow the full-scale tests to be conducted.

The regain of pressure-head due to the conversion of velocity-head in the air-stream into pressure-head at the end of a long duct, where air was taken off more or less uniformly along the whole length, was shown in *Figs. 9* of the Paper. That result agreed with what would be expected in theory, and similar results were obtained during the tests in the experimental length, where the slot openings were made

Mr. Lister.

adjustable for purposes of experiment. Those slots, set in accordance with calculations, gave almost uniform flow throughout the whole 1000 feet tested. There were measuring-stations in the duct every 100 feet, and readings were taken which showed an almost equal increment at each station. Some doubt had been expressed during the earlier discussions on the problem of the Mersey tunnel, as to the effect of foggy weather on the atmosphere in the tunnel, but he believed that, as he had anticipated would be the case, the atmosphere in the tunnel during such foggy periods was considerably better than outside, and that no traffic-delays had been caused in the tunnel by fog.

Mr. Gedye had mentioned that, when he visited the Holland tunnel in 1931, there was no longitudinal air-flow along the tunnel. When Mr. Lister and Mr. Hewett visited that tunnel, in November and December, 1929, there appeared to be a definite flow along the tunnel, and the engineer gave them a figure of approximately 10 miles per hour. A similar figure was obtained in the tunnels at Pittsburg, which were through a hill, and advantage had been taken of it in that case to use a longitudinal system of ventilation. Both the blowing and exhaust fans were placed near the centre of the tunnel, and there were separate tunnels for traffic in each direction, each single-way. The exhaust fan drew from one portal to the centre of the tunnel, and the blowing fan delivered fresh air at the centre towards the other portal, in the direction of the traffic-flow. The only trouble experienced with that system was that under certain conditions of head-wind the path of the ventilation-air was blocked by the opposing wind. A false portal was therefore built a few yards away from the true portal, and the space between acted as a form of chimney, up which the two opposing air-currents were able to flow.

Mr. Colquhoun had mentioned that the fans installed were of the centrifugal type, "which had been in use for the last hundred years," and had stated that the axial-flow or propeller-type fan had now reached a state of development when it demanded consideration. Mr. Colquhoun appeared to overlook the fact that improvements in the design of centrifugal fans had also taken place in recent years, which had resulted in a great improvement in their efficiency. He agreed that the axial-flow fan had been greatly improved recently, and that for certain purposes it was admirable, but the improvements effected up to the present had not succeeded in overcoming the trouble of noise, which he believed had been the main reason for not adopting those fans in the case of the Mersey tunnel. As compared with centrifugal fans, the amount of noise produced was very much greater. That could be understood from the fact that for equal

pressures the peripheral speed of a propeller-type fan must be very much greater than that of a centrifugal fan, and the amount of noise increased very rapidly with increase of speed. He had recently seen three or four axial-flow fans of the latest design, but they were much more noisy than centrifugal fans of equal capacity and working against equal pressure would have been. The maximum intensity of noise, which was given as 80 decibels in the Paper, was registered for a fan running at a much higher speed than was actually required in the case of the fans which had been installed. The experiments were arranged before the decision was made to omit the upper or ceiling duct; at that time it was thought that it might be necessary to have a ceiling duct, in which case a much higher water-gauge reading would have been required. At that time, moreover, it was thought that 300 cubic feet of air per foot-run of tunnel, instead of 200 cubic feet, might be necessary. With regard to the question of reliability, he did not think that that need be considered, because there should be no great difficulty in designing an axial-flow fan to run satisfactorily for many years. He would like to mention that the modern type of centrifugal fan, as exemplified in the fans which he had had the honour of designing for some of the installations, was for equal capacity only about half the diameter of the old type of mine-fan mentioned by Mr. Colquhoun. In addition, the centrifugal fan had a self-limiting power-characteristic, which was of considerable importance in cases where, as in the Mersey tunnel, there was some doubt as to the actual resistance of the completed system, as it ensured that under no conditions could there be serious overloading of the driving motor so long as the speed did not exceed the specified figure.

Mr. Colquhoun had also referred to the size of the buildings necessary to house the fans. It was necessary to remember that in the larger buildings accommodation was provided for transformers and other equipment, and the buildings were considerably larger than was actually necessary for the fans themselves.

He had been interested in the carbon-monoxide figures given by Mr. Colquhoun, because he had always been under the impression that British engines would not be quite so liberal with their emission of poisonous gases as American cars had been shown to be in the American tests. Those figures were the results of tests on more than a hundred vehicles of various types and sizes, and covered tests on cars standing with engines idling and racing, and at speeds up to 15 miles per hour on the level, up and down gradients, and both light and loaded. The figures were summarized in Table III (p. 540).

From those figures it would be seen that the average emission for those American vehicles was approximately 0.6 cubic foot per minute with engines idling, and $1\frac{1}{2}$ cubic foot per minute under

Mr. Lister.

all conditions, with a maximum, when pulling fully loaded up a 3 per cent. gradient, of 2·7 cubic feet per minute for all vehicles. Generally speaking, a car emitted from two to three times the

TABLE III.—CUBIC FEET OF CARBON MONOXIDE PER CAR PER HOUR.

Type of vehicle.	Mean of light and full load.			Full load only.		
	Mini- mum.	Maxi- mum.	Average.	Mini- mum.	Maxi- mum.	Average.
5-passenger car	29	77	52	—	—	—
7 " " " " " "	42	144	89	39	164	98
Truck up to 1½ ton	31	96	61	37	118	67
" " 1½-3 tons	15	135	80	24	150	91
" " 3½-4½ " " "	55	184	119	50	182	113
" " 5 tons and over	51	182	111	48	199	129
Average	37	136	85	40	162	100

volume of carbon monoxide when going up a gradient than when running downhill, while on the level the figure was approximately a mean between those figures.

Typical analyses of the exhaust gases were as follows :—

	On level.	Up 3-per-cent. grade.
Carbon dioxide	8·9 per cent.	9·6 per cent.
Oxygen	2·3 "	1·3 "
Carbon monoxide	6·3 "	6·4 "
Hydrogen	3·0 "	2·9 "
Methane	0·9 "	0·6 "
Nitrogen	78·6 "	79·2 "
	100·0	100·0

Actually, the figures given by Mr. Colquhoun agreed fairly well with the American figures for the lighter class of vehicle. The Americans had taken 1½ cubic foot per minute as the average for all the vehicles tested, and the ratio of heavy lorries to light cars appeared to have been almost exactly the reverse of what had been observed in the case of the Mersey tunnel. The whole subject of tunnel-ventilation was one of very great interest and importance, in view of the recent and probable future development of motor traffic, and it would remain so until an internal-combustion engine was produced which did not emit carbon monoxide.

Mr. Lister then showed some lantern-slides of the fans installed in connection with the Mersey tunnel.

Mr. Williamson. Mr. JAMES WILLIAMSON joined with previous speakers in congratulating the Author on his Paper, and said that he had been particularly interested in some of the details given with regard to the actual tunnelling, as the headings were comparable in size with some of the tunnelling-work on the Galloway water-power scheme.

The 11-foot 6-inch Glen Lee tunnel, which was completely lined with concrete, was about the same size as some of the headings described in the Paper. The rock was harder than the sandstone with which the Author had to deal, and would not blow so cleanly, whilst the charges had to be about $3\frac{1}{2}$ lbs. of dynamite per cubic yard, as compared with the figure of under $1\frac{1}{2}$ lb. given by the Author. One of the reasons, no doubt, why those large charges had been introduced was because speed was necessary, and the rate of driving ahead in that particular tunnel was, on an average over a good period, 100 feet per week. In a more recent tunnel of smaller size, where driving in rock began at the end of 1934 and was completed at the end of 1935, a length of 6,000 feet was driven from one end in a period of roughly 50 weeks, the average rate being 120 feet per week. The maximum weekly rate was something over 140 feet, or 1 foot progress for every working-hour. Those water-tunnels were very small compared with that which the Author had described, but there was also a short length of tunnel of a larger size, 22 feet in width by 18 feet in height, to carry water through under pressure. The rock was considerably jointed, and the whole of the rock at the back of the concrete lining was grouted.

The cost of that tunnel worked out at just under £30 per linear foot, and it was estimated that the completely-lined rock-tunnels would cost, for the smaller sizes, about £1 per linear foot for each foot of diameter. For the larger sizes the cost would be greater; in the case of the 22-foot tunnel to which he had referred, the cost per linear foot would be about £1 $\frac{1}{2}$ for each foot of diameter. That tunnel was nearly large enough to take two lines of traffic, and he had made a rough calculation that in similar circumstances, with a completely-lined concrete tunnel big enough for two lines of traffic, the cost would work out at from £50 to £60 per foot. Those conditions were widely different from the conditions with which the Author had had to deal under the river Mersey, where there was a high pressure of water to deal with; it had, however, occurred to him that, as had already been suggested, even if a cast-iron lining had to be used, two tunnels each arranged for two lines of traffic would probably have worked out more cheaply. If compressed air had been required he thought they would certainly have been more favourable from the point of view of construction, as the bottom of the tunnels could probably have been some 18 feet higher than the bottom of the larger tunnel.

Mr. T. H. WEBSTER remarked that he would like to ask one or two questions on matters which might have puzzled others besides himself. With regard to the cast-iron lining, the Author had said that the top half was put in first. He could not understand how the

Mr. Webster. lower half was then put in without the top half falling down a certain amount.

There were fourteen different headings or "break-ups" and a cast-iron lining was put in each heading. Unless that lining were very accurately started in each one of those headings, trouble would arise when the cast-iron linings in the headings met, and it would be of interest to know with what degree of accuracy those headings met. When fourteen headings met in thirteen different places there would be thirteen joints, and he wondered whether any trouble had arisen in connection with the axes not being coincident in all those cases.

The Author. The AUTHOR, in reply, said that a question which had been raised by several speakers was why one tunnel of large diameter had been adopted instead of two tunnels of smaller diameter. There were a number of reasons for that, one being that it was desired to have a broad thoroughfare, like Dale street, joining the two towns. From a spectacular point of view, and certainly from the point of view of general airiness and flexibility of traffic under exceptional conditions, one large tunnel carrying four lines of traffic, provided that it was not too expensive, was to be aimed at rather than two separate tunnels each with two lines of traffic. If the tunnelling had had to be done through bad ground or soft ground, he admitted that it would have been necessary to adopt separate tunnels, but the tunnelling was done through continuous sandstone-rock, which lent itself readily to large-scale excavation. Another point to be borne in mind was that, in fact, accommodation for six lines of traffic had been provided; there were four lines of traffic on the horizontal diameter, and there was room for two more lines of traffic in the space underneath, which was 21 feet in width and about 17 feet in height. It would, therefore, have required three separate tunnels, each with two lines of traffic, to afford a fair comparison with the one large tunnel which had been constructed.

A problem which, however, arose was that of the branch tunnels. It was a feasible engineering proposition to take a small branch tunnel out of a large main tunnel, but considerable difficulties would be found if an attempt were made to take a branch tunnel out of another tunnel of the same size. That led him to the statement which had been made to the effect that there was an interruption of traffic where the branch tunnel diverged from the main tunnel. That was true, and fly-under and fly-over junctions had been considered; but, with one gradient seeking to connect with another gradient it became an extremely difficult piece of work, and, while either would have given more uninterrupted running, it was found necessary to adopt the junction chambers that were ultimately constructed.

There was another point to which he would like to refer : namely, *The Author.* the capacity of the tunnel. The tunnel, so far as ventilation was concerned, had been designed on the basis of a dilution of 2·5 parts of carbon monoxide per 10,000 parts of air, and on the assumption that 12,000,000 vehicles per annum would ultimately use the tunnel. At the moment, only about 3,000,000 vehicles were using it, and the carbon monoxide, with the fans only running at half-speed, was about 1 part in 10,000 at present. The 4 parts in 10,000 to which Dr. Lowe-Brown had referred could occur only in a time of panic. If there happened to be a panic, and vehicles were left in the tunnel with the engines running, it might be possible for the dilution to reach 4 parts in 10,000 ; but even under those almost absurd conditions—but conditions which, nevertheless, had occurred in the Pittsburg tunnel—the ventilation plant would keep the dilution at 4 parts per 10,000, and it would still be safe to go into the tunnel and to shut off the engines.

Mr. Peirson Frank was quite right in drawing attention to the fact that the tunnel as actually built was considerably longer than that in the design originally placed before Parliament. The additional length was one of the reasons why the cost had been greater than the original estimate.

With regard to the section of rubber-surfaced roadway, it was situated on a bend, and not far from the open portal ; some skidding did take place, due partly to the wheels of cars bringing water in with them and so wetting the surface, and also because strangers to the tunnel were apt to apply the brakes of their vehicles somewhat suddenly when they saw a change in the surface from the cast-iron paving.

In connection with the cementation-process, pressures of about 200 pounds per square inch were used at first, but were found to be too high, as the cement got into the horizontal layers, and tended to lift the immediate neighbourhood. Pressures were then reduced, so as to balance the hydrostatic head of the water in the rock.

The whole credit for the introduction of the suspended roadway lay with the contractors, and he doubted whether the progress that had been made could have been achieved without it.

The figures given in Table II by Mr. Colquhoun were of very great interest, as they showed that, in spite of all the difficulties that had been encountered, the Mersey tunnel compared very favourably in cost with other tunnels. The Author agreed with the reference to propeller-type fans, and he thought that such fans had now reached such a stage of development that they would have to be very seriously considered in connection with future tunnels, and that considerable economies would result from their adoption. Unfortunately, when a decision had to be made regarding the fans for the Mersey tunnel,

The Author. the propeller-type fan had not been sufficiently developed to justify its adoption.

The remarks regarding the use of structural steel and concrete in place of cast iron for the lining of the tunnel were very interesting. The Paper showed that, above the water-table, rolled-steel joists and concrete had been used, and quite considerable economies had been effected. In the under-river portion, where the water-pressure was of the order of 80 pounds per square inch, the engineers had decided that cast iron must be adhered to, not only because of its practically everlasting qualities, but because it could be made absolutely water-tight. The whole question of an alternative to cast iron was under very careful consideration by the engineers as regards other tunnels, and, in particular, in connection with the tube-railways of London.

The Author was very anxious to try out reinforced-concrete and steel linings, but the questions of durability, ease of erection and ease of attaching fittings to the lining all had to be borne in mind.

As regards the thickness of $1\frac{1}{2}$ inch for the skin, that was more of a problem of casting than one of strength; the thickness of $1\frac{1}{2}$ inch was judged to bear a proper ratio to the thick and deep flanges, and to eliminate the cooling stresses as much as possible.

In order to keep the length of the Paper within reasonable limits, a great many details had perforce been omitted, and the Author would gladly consider the suggestion put forward by Dr. Lowe-Brown that further Papers might be submitted to The Institution by members of his staff and others connected with the work.

* * The Correspondence on the above Paper will be published later; the Author, in his reply thereto, will deal further with certain points raised in the Discussion.—SEC. INST. C.E.

ORDINARY MEETING.

16 March, 1936.

Mr. JOHN DUNCAN WATSON, President, in the Chair.

The discussion on the Paper by Mr. Anderson on the Mersey tunnel was continued and concluded.