THE AIR AND VENTILATION OF SUBWAYS

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CHAPTER I

SUBWAYS AND THE PUBLIC HEALTH

The development of subways as a means of facilitating the movement of people from point to point within the limits of a single city forms an interesting chapter in the history of modern transportation. Placed in the last few years upon a successful basis as a result of operating and structural devices not before practicable, nearly all the largest cities now possess one or more subways and scores of smaller places are planning them.

In the construction of subway systems, London, the most populous city, has at all times held first rank. Not only were the first subways built there, but, in face of repeated failure, subway construction was persisted in in London until it became a popular success. To-day there are more types of subways in London, and a greater aggregate mileage of them, than can be found in any other city.

EVOLUTION OF THE MODERN SUBWAY

The first important tunnel built solely for the transportation of passengers from one part of a city to another ran under the Thames in London about two miles below London Bridge. The object, as in several other river tunnels which were built in early times, was merely to afford means of passing from one shore to another and not to connect with any surface transportation system.
This first subway was begun in 1824 and was opened in 1843. The cost was about $2,340,000. It was intended for horse-propelled vehicles as well as foot passengers. It was 1200 feet long, 14 feet wide and 16 feet 4 inches high. There were, in fact, two parallel tunnels of these dimensions, running side by side, separated by a masonry pier 4 feet thick. The undertaking paid so poorly that the receipts were scarcely sufficient to meet the cost of repairs. This road now forms part of the East London Railway having been purchased in 1865 for less than one-half the original cost.

The first subway to be provided with its own vehicles for transporting passengers was constructed in 1863 under the Thames near the Tower Bridge. This tunnel was a circular iron tube composed of segments bolted together and was 7 feet in diameter and 1350 feet long. As in modern tube railways, passengers were taken up and down in elevators through shafts. These were 10 feet in diameter and 60 feet deep. Transit from one end of the tunnel to the other was accomplished on a single track by means of cars hauled by wire ropes. This subway was closed to passengers in 1897 and is now used for a gas main.

In view of the failure of these two tunnels to meet popular favor, it is interesting to note the complete success of the Blackwall tunnel which runs under the Thames about six miles below London Bridge. It was opened in 1897 and is used by passengers and pedestrians. The total length is 6210 feet, of which 1740 feet are approaches. This tunnel is next to the largest shield-driven tube in existence, being 27 feet outside diameter. The inside is lined with light-colored glazed tiles and is paved with granite blocks on the inclines and with asphalt elsewhere. It is well lighted and the air is agreeable, ventilation taking place through large shafts on the two opposite shores.
The first extensive underground railway which can properly be termed a system was the Metropolitan and District of London. Its object was to carry the public more expeditiously and comfortably from place to place within the city than could be accomplished on the surface. This road was opened from Paddington, the terminus of the Great Western Railway, to Farringdon Street in the business district, in 1863. Extensions were numerous up to 1884, at which time the system had been so developed as to form a complete circle around the inner portions of the city.

To-day, the Metropolitan is almost the only example in London of a shallow railroad subway, that is, one built near the surface of the ground and reached by stairways. All the rest, and there are six more, have been built in the London clay at depths which vary from 40 to 150 feet below the surface.

The pioneer deep tube subway under city streets was the City and South London and was opened for traffic in 1890. It is about three miles long and, like practically all deeply lying roads, is composed of two metal-lined tubes running side by side. This road has been very successful, carrying in the first year of operation about 2,400,000 passengers. It was the first important city subway to be operated by electricity. The original intention was to use an endless cable for moving the trains.

**New London tubes.** By far the best known and one of the most profitable deep subways is the Central London which was opened in 1900. After this came the Great Northern and City, opened in 1904, the Waterloo and City, the Baker Street and Waterloo, the Great Northern, Piccadilly and Brompton and the Charing Cross, Euston and Hampstead.
The average internal diameter of these deep tubes is 11 feet 6 inches. They occasionally follow steep grades and curve about continually. The different roads are frequently connected at stations by passageways for foot passengers.

**Paris subways.** Following the example of London, the city of Paris, in 1898, laid out an elaborate plan for subways. The road was built to relieve the lack of public transportation facilities in Paris itself and to develop poorly populated and distant quarters in the suburbs. It was at first thought that only a part of the whole plan would be carried out, but the success which followed the opening of the road was so great that it was at once decided to finish the entire system. Passengers were first carried in 1901.

Unlike most of the London roads, the Paris subways belong to the type which runs close beneath the surface of the ground, are built of masonry, have two or more tracks and are reached by stairways from the streets. Since the opening of the Paris system, extensive construction has been in progress both by the city and by private capital, so that, at the present time, Paris has the second greatest aggregate underground railroad mileage of any city.

**Berlin subways.** The city of Berlin is provided with a combined subway and elevated system which was opened for traffic in 1902. It is one of three roads which run partly overhead and extends through the central part of the city from east to west. The tunnels were constructed under the streets, the top sometimes approaching to within 2 feet of the surface. The subway system was considerably extended in 1907.
Other European subways. The city of Budapest has an electric underground railway about two miles in length opened in 1896. It is a double-tracked, overhead trolley system built near the surface of the ground and in design resembles the subways of Boston, New York and Philadelphia.

Glasgow has a subway six miles long partly of the deep, and partly of the shallow, type.

Many other important subways now exist in Europe. Some belong to the period of earliest construction, while others are of a newer type. Nearly all are operated by electricity.

American subways. Aside from the terminal connections of trunk line railroads, the first underground city railroad in America was built in Boston and was begun in 1895. This road runs under the business part of the city with a branch under the harbor and accommodates several lines of trolley cars as well as trains of the Boston Elevated System. It is not provided with its own cars but is used by outside lines which otherwise would run on the surface and interfere with street traffic. It was estimated that at least 50,000,000 passengers used the original subway during the first twelve months after its completion and its use has apparently increased since then by over 60 per cent.

The New York subway was opened in 1904. It was considered to be the most perfect example of subway construction yet afforded and was expected to play an important part in relieving the congestion which is rapidly growing at the southern end of Manhattan Island. It is, like most subways, chiefly of the shallow type. A description of its principal features will be found beyond. (See Figs. 1 and 2.)
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Fig. 1. Route of the New York subway
An account of the plans for the development of underground and under-water transportation in New York which have followed the opening of the first subway would pass the limits of space of this volume. They include roads under the Hudson river and East river and extensions of the original line aggregating many miles in length.

The history of the construction of city subways shows that although underground roads were built over fifty years ago, it was not until electric traction became practicable, bringing with it the possibility of good air, that city subways on a large scale were successful. It is interesting to note that the key to success depended largely upon the question of sanitation. Subways could not be made even tolerably agreeable so long as it was necessary to light them by oil and propel the cars by means of coal-burning locomotives. To such conditions no public could be expected to become indifferent. On this point the history of the Metropolitan of London is conclusive.

Underground adjuncts of subways. In the rapid growth of subways which has here been outlined, the construction has not been confined to the simple form of structure originally adopted. Both with respect to main lines and auxiliary passages, developments have been made which are of considerable interest when viewed from a sanitary standpoint.

The New York subway differs from most foreign roads in having four tracks instead of one or two, in being provided with express as well as local services, in having underground stations with elaborate toilet room facilities and in having numerous underground connections with office buildings and shops. These lateral connections sometimes run for considerable distances through the basements of sky-
scraper office buildings, hotels and shops. The passages often accommodate barber shops, restaurants, news stands, fruit and candy stands, soda fountains and flower booths.

The lateral underground passages of the deep London tubes are often long and devious, but they are used only by pedestrians and do not contain shops. On the station platforms of practically all subways are automatic vending and weighing machines. The articles sold are innumerable in variety.

It is needless to remark that in all these lateral subterranean passages the sun never penetrates and it is always night. Fresh air enters only through doors and through elevator shafts. The air is usually cool. The volumes of air passing are often very large. Where candy, fruit and other food is sold it is usually quite unprotected from the dust and air.

**Effects of subways on congestion of population.** It would be interesting, if space permitted, to discuss the effect on congestion of population which the construction of underground railroads for urban intercommunication has produced. It would be seen that the ultimate effect has been quite opposite to that sometimes intended, for, instead of relieving congestion, they have increased it. If the subways have given new outlets from the overcrowded sections of cities to the more sparsely settled ones, they have also provided means by which the overcrowded places can be more rapidly reached than formerly, with the result that the worst places have been still further congested. This added congestion means serious inconvenience and possibly injury to the public health.

Some of the inconvenience which results from congestion is but too evident to every person who visits the business
districts of a great city during business hours. The streets
are so crowded that pedestrians overflow from the side-
walks upon the carriageways and there is so little room on
the carriageways that vehicles are able to thread their way
only with difficulty and at greatly reduced speed.

Nor does the effect of this crowding bear only on the
mere convenience of the public. It interferes seriously
with the conduct of trade. This means loss of money.
Sir John Wolfe-Barry ¹ and Mr. R. G. H. Davison have cal-
culated that the loss of time experienced through the con-
gested condition of London streets affects persons whose
annual aggregate earning capacity is £173,291,000 and of
vehicles whose time is valued at £16,562,000 annually. If
the loss of time to each one of these wage earners is only
five minutes in each day of eight hours, the total loss in
money which would be produced in a year would be
£1,898,534. It is not improbable that the actual loss is
much greater.

Careful studies in America and Europe as to the causes
and remedies for overcrowded streets have been carried on
by a Royal Commission on London Traffic, and an advisory
board composed of Sir John Wolfe-Barry, Sir Benjamin
Baker and William Barelly Parsons, engineers of inter-
national reputation, have shown in a report to this com-
mission that by bringing more and more people from the
immediate suburbs, the development of city railways has
increased congestion to such a point that it is now necessary
to widen streets, plan for proper sub-structures beneath
the streets and regulate the heights of buildings if more
serious consequences to the commercial welfare of the city
are to be avoided.

¹ Memorandum by Sir John Wolfe-Barry, K.C.B., and Mr. R. G. H.
Davison, M. Inst. C. E. in Appendix to Report of Advisory Board of
Physical principles involved in subway heating and cooling. The heating of subways affects the comfort of the travelling public to such an extent that it may be well briefly to refer here to some of the physical principles which must be taken into account in disposing of the heat.

The warm air of a subway is due to the heat produced by the machinery and brakes on the trains. The heat generated from the bodies of passengers is inconsiderable when compared with the amount which is due to the consumption of energy used in operating the trains. Were it not for the mechanical losses due to the production and transmission of the electric current, the heat produced in a subway would be the same as though the coal used up at the power house was consumed in fires along the track.

The only way for the heat to disappear is to escape through the walls or by the air.

When hot motors and brake shoes pass through a subway they lose their heat by radiation and conduction, the large volumes of air which flow over them greatly favoring the removal of heat in the latter manner. The heating of rooms by stoves and steam pipes occurs largely in the same way; in this case, however, the air is brought into contact with the hot surfaces chiefly through currents set up by the

Also from Dr Soper’s book of 1908
heat itself. The action of these currents constitutes a special form of conduction called convection.

The walls of a subway become heated through the direct effect of radiation from the trains and by absorbing heat from the air and they transmit the heat to the cooler earth beyond them. The rate of transmission, called thermal conductivity, differs with different substances. The rate varies, also, with the thickness of the body through which the heat is transmitted and the difference of temperature at the two sides.

When subways are first put in operation much of the heat produced by the cars is transmitted through the metal and masonry linings to the earth surrounding them, but in course of time this earth becomes warm also, and little more heat can be absorbed. The subway air then grows warmer and unless some special means of removing the heat is provided, the air may become very uncomfortable. The most practicable means of cooling a subway is to provide for a very large amount of ventilation.

PRACTICAL SYSTEMS IN USE

The ways in which subways have been ventilated may conveniently be considered under four separate heads:

1. By introducing or exhausting air at various points by means of fans.

2. By forcing a current of air from one end to the other of the whole line by fans.

3. By so-called natural ventilation.

4. By the piston action of trains.

The exhaust and plenum principles. Fans are almost invariably employed to exhaust air, not to supply it. They
may exhaust through side chambers directly to the outside air, as in the older portions of the Boston subway, or by means of air ducts communicating at various points, as in the Severn and Mersey tunnels. In the former case a number of comparatively small ventilating fans are employed at the points where the air is to be extracted; in the latter, large central pumping plants are used. In any case fresh air is expected to enter at stations or other appropriate points as rapidly as the foul air is exhausted.

In the plenum principle the fresh air is forced in by the fans and the foul air escapes as best it can. This method is more often used to supply air during construction of deep subways than in subways after they are built.

Many arguments have been brought forward to show the advantage of renewing the air at stations rather than elsewhere.

It has been urged, for example, that the air should be exhausted between stations and allowed to flow in at the stations since (a) more passengers are congregated at stations than at other points and in this way they will get the freshest air; (b) the air in the cars is renewed at stations not between them, so the air should be at its best there; (c) this method would most rapidly remove smoke and heat in case of fire and give the best opportunity for escape through the stations.

Some of these arguments are valid while others involve refinements of logic which seem scarcely justified. If the air is renewed as frequently as it should be, it makes little difference from a sanitary standpoint at what places it is introduced or exhausted.

1. **Action of fans applied at various points.** The earliest use of a fan for assisting the ventilation of a railway tunnel


is believed to have been in 1870 in connection with the Lime Street tunnel of the London and Northwestern Railroad at Liverpool.

Following the generous proportions of fans which had been employed in ventilating mines, this fan was 29½ feet in diameter and discharged its air into a conical brick chimney 54 feet in diameter at the base. The quantity of air thrown was 431,000 cubic feet per minute. The air was taken from a point midway between the two ends of the tunnel. The tunnel was 6075 feet in length.¹

Fans in the Boston subway. The Boston subway is about 4½ miles long and is operated by electricity. It is used by trains and single trolley cars, most of whose routes lie in the open air. The speed is so slow that the ventilating currents set up by the moving cars are often scarcely noticeable. The typical section is 332 square feet where the subway is occupied by two tracks and 707 square feet where it is four tracks wide.

In the section of the road first built ventilating fans are placed in chambers alongside of the subway at points between stations and the air is discharged upward through grated openings in the sidewalks overhead or through short shafts to the outer air. The fans are 7 to 8 feet in diameter. They were intended to be of such capacity as to enable them to completely renew the air every ten minutes. Fig. 3.

In the section under the harbor the same general plan is followed of taking air in at the stations and removing it between stations. In this case, however, an exhaust duct has been placed along the top of the tunnel with occasional openings which can be opened or closed at pleasure. The cross section of the duct is about 48 square feet; the open-

ings are about 4 feet long and 1 foot 5 inches wide and they are placed at intervals of about 550 feet.

The air is withdrawn at each end of the tunnel and exhausted by means of fans through shafts about one mile apart, on the opposite shores. At the East Boston end

**Fig. 3. Method of Ventilating the Boston Subway with Fans.**

the air is exhausted through grated openings in the sidewalk 40 feet long and 7 feet 1 inch wide. At the other end the air is discharged about 21 feet above the surface of the street.

The fans consist of two 8 foot vertical fans at the East Boston end and two 7 foot horizontal fans at the Atlantic
Avenue shaft. At 175 to 218 revolutions per minute and about 12 horse power each, the total rated capacity of the whole ventilating plant is 90,000 cubic feet per minute. This gives a theoretical velocity for the whole air in the tunnel of about $2\frac{1}{2}$ feet per second and is equivalent to a renewal of the air every 15 minutes.

A complete description of the ventilation arrangements of the Boston subway has been given by Mr. H. A. Carson, M. Am. Soc. C. E., Chief Engineer of the Boston Transit Commission in the Proceedings of the American Society of Mechanical Engineers, Vol. 28, pp. 927–942.

*Fans in the Severn and Mersey tunnels.* The Severn tunnel, of the Great Western Railway, was opened in 1886. It is about 4½ miles long. It is occupied by two tracks for steam railway travel. There is a ventilating shaft located near the center through which air is exhausted by means of a fan 40 feet in diameter. It is said that the capacity of the fan is sufficient to renew the air of the tunnel about every ten minutes. (See Fig. 4.)

The Mersey tunnel, connecting the cities of Liverpool and Birkenhead, is about 2 miles long and is occupied by a double line of electric railway. Air is exhausted through numerous passages communicating with ventilating galleries which lead to exhaust fans. These fans are from 12 to 40 feet in diameter and are located at stations above ground. The combined capacity of these fans is estimated to be about 950,000 cubic feet per minute or sufficient to renew the air of the tunnel every nine minutes. This tunnel is often referred to as affording an example of the most perfect system of artificial ventilation yet devised. It was certainly the earliest tunnel in which a comprehensive system was adopted. (See Fig. 5.)
Fans in the newest London tubes. The general plan of ventilating the new tubes of the Electric Underground Railways Company is to take advantage of the piston action of the trains, as do all the London subways, and to supplement this by fans at the stations.

The fans exhaust air from beneath the station platforms.
and carry it through airways averaging 12 to 16 feet in
cross section to the roofs of the buildings used for subway
stations; there to be discharged into the free atmosphere.
The fresh air enters through these station stairways and
lifts. (See Fig. 6.)
The fans are of a designed capacity sufficient to remove
1,000,000 cubic feet of air per hour when working at
moderate speed. This is sufficient to renew all the air in
the average length of subway between two stations in each
of the parallel tunnels every thirty minutes. The fans are
located at the tops of the buildings. They have been
found, upon test, to deliver 18,250 cubic feet per minute
when operated at a velocity of 242 revolutions per minute.
Great care was used to avoid vibration and noise from the
motors and fans.

2. Action of fans applied at one end of a subway.—
System used by Central London Underground. A system
of forcing air through an electric subway has been in-
stalled in connection with the Central London Under-
ground, a good example of the deep London tubes.
The ventilating arrangement of the Central London
Railway is capable of renewing all the air contained in this
subway three times over every night. In order to accom-
plish this result double doors are arranged at the station
entrances and shut at night. The air flows in at the city
end of the Bank of England, passes through the two tubes,
each over six miles long, and is exhausted by a fan at
Shepherd’s Bush.
The fan is 20 feet in diameter, of the Guibal type. It
is said to be capable of exhausting 100,000 cubic feet of
air a minute as measured at a point near the far end of the
line. During the day it is not possible to run this fan with
much effect, because, with the opening of the station doors by passengers, it draws air from the stations, chiefly from the nearest one. But at night after the last train has been run out of the subway on the surface at the west end all the doors are closed and the fan is started. It is kept going until the first train is run in the morning. The results are said to be excellent.

3. **Natural ventilation.** Although many subways are now provided with some system of ventilation requiring the use of fans, by far the greatest number still depend for a circulation of air upon currents set up without special mechanical aid.

*Blow-holes.* Among the more common ways of securing this so-called natural ventilation, the use of blow-holes, or free openings to the outside air, deserve special notice. It is to ventilation accomplished in this way that the frequent renewal of air in the New York subway is due.

The draught of air passing through the blow-holes is sometimes violent. An average velocity of 16½ miles per hour through the stairways of the New York subway was observed in the author's investigations as a result of several hours' observation with anemometers. Had this current taken place through one-half of the openings between 96th Street and the Brooklyn Bridge the quantity of air so supplied would have been capable of renewing the entire atmosphere of the subway every few minutes.

At first sight it would appear that nothing could be easier than to ventilate a subway by this means. It seems as simple as opening the window of a living room. Yet to get the best effects from blow-holes, ventilation means much more than the mere opening of the roof. To provide for a suitable and reliable movement of air requires careful
study. Apparently the very simplicity of the idea of blow-hole ventilation has prevented the development of this principle in the best manner. To some subways and tunnels it is peculiarly suited.

The term blow-hole is here used to include all openings through which the confined air can escape and fresh air enter, whether they be stairways, openings in the roof or openings through side chambers. In shallow subways such openings usually pierce the roof or lead from station platforms with more or less directness to the outside air. They are usually much too small, too indirect and too long to accomplish all the benefit which may be obtained from them.

Inasmuch as the flow of the air is impeded by friction against the walls, blow-holes should be as short as practicable. Since the friction increases as the square of the velocity of the current and inversely as the diameter of the passage, they should be large in section and but little obstructed by screens, doorways, nettings and other incumbrances.

It is easy to see that blow-holes may be more advantageously employed in subways built near the surface of the ground than in railways far beneath the surface. And yet this is the only way in which some of the deep London tubes are ventilated.

*Direction of openings with respect to wind.* If, as sometimes happens, the blow-holes are open stairways covered by cowl-like kiosks, the direction of the openings with respect to prevailing breezes may materially aid or interfere with the amount of air which passes in or out. Let us briefly examine this effect.

A breeze which is just perceptible may be assumed to travel at a velocity of 2.92 feet per second and to exert a
pressure of 0.02 pounds per square foot and a breeze of twice this velocity exercises four times this pressure. A brisk wind travelling at a velocity of 25 miles per hour or 36 feet per second, a not uncommon occurrence in New York at some seasons of year, exercises a pressure of about 3 pounds per square foot. A wind of 45 miles exercises a pressure of 10 pounds. If a pleasant breeze of 2½ miles per hour acts full upon a kiosk such as many of those which stand over the New York subway, measuring $5\frac{1}{2} \times 7\frac{1}{2}$ feet, it is as effective as two fans, each 6 feet in diameter, turning at the rate of 200 revolutions per minute and delivering 21,200 cubic feet of air per minute.

4. **The piston action of trains.** The action of moving trains is more important than any other factor in establishing a circulation of air through blow-holes. This so-called "piston," or "plunger" action has long been recognized as useful, but it has remained for the New York subway to demonstrate how extremely beneficial it may be.

The main principle of the phenomenon of piston action is easily understood. The moving trains force air ahead of them and cause air to rush in after they are passed.

The action is probably to be regarded as a combination of the principle of a fan in which there is practically no displacement and the principle of a plunger in which the displacement produces the whole effect. The plunger action is greatest at stations and other enlargements of the subway and where the speed is slow. The fan action is most important where the speed is high and where the train fits the subway most completely.

The quantity of air moved depends upon many circumstances. Chief of these are (a) the extent to which the
tunnel section is filled by the section of the train; (b) the speed of the train; (c) the opportunity afforded by blow-holes for the air to flow in and out; and (d) the shape of the forward end of the train. These facts seem too obvious to need discussion.

*Berlin-Zossen tests.* In studies made on the Berlin-Zossen Railway into the resistance offered by the free outside atmosphere to the movement of trains, it was found that air piled up in front of the first car in the form of a cone of increased pressure and that a cone of reduced pressure followed behind the train. For example, the pressure in front of a car (which presented a face perpendicular to the line of the track) was 4.09 pounds per square foot at a speed of 12.4 miles per hour; 6.14 pounds at 18.6 miles; 8.19 pounds at 24.8 miles. This pressure was maintained for between 10 and 16 feet in front of the moving train; beyond this it gradually fell off.

*Official observations in Paris subway.* A Commission appointed by the Prefect of the Seine to study the ventilation of the Metropolitan Subway of Paris gave some attention to the air currents which circulated about the trains. The air flowed ahead of the train until the front of the train was immediately opposite the observer, when there was a sudden gust and the flow changed to a direction opposite that of the train movement. After the train passed, air followed it for about one minute. When the train moved at the rate of about 3 feet per second, less than 2 miles per hour, air 165 feet ahead of the train moved at about the same velocity.