The Maintenance of The London Underground Tube Tunnel Network

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Introduction It is helpful to have a brief history of London Underground when considering any aspect of its maintenance or future development. The system has developed over more than 100 years and only comparatively recently come under the control of a single organisation. This partly explains the complexity that has resulted from differences in construction between lines. A brief History is accordingly appended to this presentation as Appendix B.

The recent History outlines how Tube Lines have come to be involved with London Underground and explains a little of the reason for our existence.

We are required to maintain and improve London Underground assets. Our performance has to be measurable and it follows that we need to know the current condition "value" of those assets.

A large part of London Underground's infrastructure is tube tunnels some of which have not been fully assessed since they were first constructed in the 19th Century. They used materials whose physical and durability properties were not, at the time, fully understood; and they were designed on a very empirical basis if they were "designed" at all.

Some shafts and other elements of the Tunnel Asset appeared to have been forgotten or lost when the Public Private Partnership (PPP) instigation procedures began in earnest in 1998.

A major part of our current maintenance programme is thus to ascertain and agree the current condition and extent of approximately 178kilometres of tube tunnel asset that we are required to maintain and improve.

The Essential Maintenance Issues

The principal alteration in maintenance philosophy is the step change from

"Make do and mend" The process of reacting to observed weaknesses in the network sufficiently only to keep the railway running safely. It required a lot of "engineering judgement and experience" and proved surprisingly successful but did not lead to improvements.

To "Evaluate, maintain and improve asset value". This process is necessary to encourage investment and development of the system. It establishes an accurate knowledge of current condition to provide a base line against which progress and improvement can be measured. It also gives us the ability to plan our maintenance by identifying current and forecasting future problem areas. Exploration (inspection), measurement, testing, knowledge of physical and chemical properties of the materials used and the soils environment, and research are all required.

Other maintenance issues exist within that basic framework. They are brought about by changes due to development within or near to the assets that we maintain e. g. provision of a new cross passages or driving a new LUL tunnel under an existing one, or work by outside (third) parties e. g. a new multi storey piled structure affecting our tunnels.

The Procedures

Analysis

This paper does not set out to impose a method of assessing or analysing the tunnels. The author is of the opinion that provided a rational and consistent approach is made with appropriate safety factors adopted any analysis will provide a reasonable indication of condition, safety, need to repair and areas of priority.

The determination of appropriate parameters for use in the adopted analysis is however of significance and needs to be determined by inspection, sampling and testing.

The approach currently adopted by Tube Lines is outlined in Appendix A "The Tube Lines Project."

Inspections (past)

Traditionally in London Underground track was inspected every 24 hours, and cast iron tunnel linings once every 12 years. These periods were not chosen randomly they had been determined by experience of deterioration rates and priorities related to keeping the railway in operation. Special additional inspections linked to assessments were of course necessary where known changes were taking place, in reaction to specific incidents.

Clearly that process needed to change. It not only implied that some of the tunnel assets may not have been inspected for 11 years prior to Tube Lines assuming responsibility, but also that for some tunnels only two inspections would be required during the whole of Tube Lines′ "tenure". This is not a procedure whereby improvement can be measured and is therefore no longer acceptable.

Inspections within tunnels have generally been walk – through visual checks except where they constituted reactions to reported events e. g. an increased level of water ingress, cracked finishes, clear movements between inspections or other indications of structural distress.

The "Old Street" experience was an example of both good and bad aspects of such an inspection regime and the need to follow through initial discovery with detailed consideration of cause before arriving at a proper conclusion.

Inspections (present)

For reasons stated above it is now necessary to get behind the finishes, possibly behind the linings, to ascertain exactly the conditions that exist and to assess the whole asset. To determine not only that it is stable but to provide estimates of its residual life (i. e. Statements of how long elements of the asset will last before repair or replacement is necessary).

For the commercial and investment reasons discussed earlier it is now necessary to expand our inspection regime several fold.

The current inspections are required to provide a complete classification of the condition of the Tube Tunnel Asset before the end of a 7.5 year period starting from 2003, the beginning of Tube Lines responsibility. This will require complete inspection and assessment of every section of the Tube Tunnel asset that falls under Tube Lines remit. Every tunnel (station & running), junction, cross – passage and supporting steelwork, every shaft (including escalator shafts), every head wall and etc. etc. The materials used in the construction of each element will come under similar scrutiny, as will the surrounding soils, back – grouting environment, water levels (existing and anticipated) etc..

This will necessitate making full use of every opportunity presented by for example track closures and Station upgrades where removal of finishes could provide access to areas not seen for 100 years.

There will also be a requirement for some coring, boring, and other forms of destructive testing.

Non destructive tests are similarly part of the inspection plans proposed. Ultrasonic tests, and sampling and testing through grout plugs are all under consideration.

Areas where problems are anticipated will be pushed forward in the inspection programme, so that all necessary or possibly urgent repair work can run in parallel with the overall inspection programme.

Once the existing condition has been established we will be in a position to make our assessments, discuss and implement future maintenance programmes and improvements.

Inspections (future)

One of our major lessons for future tunnel design requirements is that in order to comply with the Construction Design & Management (CDM) regulations in the UK it is essential that safe provision is made for inspection during the whole life of a structure. The same regulations also require a safe system for dismantling and demolishing a structure at the end of its useful life.

In future station finishes will need to provide access for inspection of the structure into account. It might also be seen to be appropriate to provide soil sampling and lining inspection access at intervals along a tunnel. Clearly this will all be supplementary to the systematic keeping of data in the "safety file".

The task of future inspections of the existing London Underground network will be eased by the present inspection programme. We will have seen and assessed the results of 100 years "wear and tear" on the tunnels during our concentrated 7.5 year study. Hopefully we will also have made all reasonable access provision to ease the task for our successors. Above all we will have recorded everything that we have found.

Modern technology could perhaps provide us with "intelligent" tunnels that would emit signals (perhaps a long groan, shriek, or cry for help) when particular strains are exceeded, or if one sensor moves too far from its neighbours.

Assessments

In the past assessments were carried out only when a problem was believed to exist or where changes to the structures were proposed. We need not concern ourselves too much with those past procedures although the resulting work carried out on the tunnels will add to the list of variables that we currently need to review.

Our proposed analysis and assessment procedures are outlined in Appendix A. The most critical aspect of any assessment procedure is that the methods of analysis, assumptions and all the background are recorded and retrievable.

Analysis fashions change not only with the passing of time but also from one country to another but provided records are complete no problems result.

Conclusions

Lessons that can be learned from the past and implemented during the current exercise are:

· To maintain precise records of the current exercise, the condition discovered, the location, the tests carried out, the analysis undertaken, and of course all relevant results.

· To provide, wherever practicable, access so that future inspections can be made with comparative ease, and certainly without the need to dismantle areas of Stations

· The day will might come when we need bigger tunnels and bigger trains. Keep this sort of idea alive. Try to foresee what problems the future may hold.

· To look very closely at CDM / HMRI regulations (or similar) with regards to the future. Tunnels may not last forever and what do we do with them when they are old, tired, and their function obsolete?

Appendix A

The Tube Lines Project

1. Introduction

Under schedule 3 of the PPP contract between London Underground Limited (LUL) and Tube Lines Limited, Tube Lines are required to carry out assessments to LUL Engineering Standard E3322 A2 Deep Tunnels and Shafts Assessment ', to " good industry standards". These assessments are to be carried out, by the end of the First Review Period. In addition Tube Lines is required to improve the knowledge and understanding of their deep level tube tunnel assets by the end of 2008.

In January 2003 a Scoping and Investigation Report (1) was produced, setting out the knowledge required and the exemplar assessments to be done in order to complete the assessments. Currently the Tube Lines Projects Department is carrying out preliminary desktop assessments of deep level running tunnels on the Jubilee, Northern and Piccadilly line, some 178km. This first stage of the assessments is a desk study exercise reviewing in detail tunnel construction, lining type, known defects, depth, geology and related geotechnical parameters. In addition first assessments are being carried out to E3322 A2.

From the scoping, investigation and desk study work carried out to date, it is possible to set out the process for assessing deep tube tunnels.

2. Aims and Objectives

Aims

To set out the process for assessing all deep tube tunnels to LUL Engineering Standard E3322 A2 Deep Tunnels and Shafts Assessment′and Schedule 3 of the PPP Contract.

Objectives

(i) To set out the method for running tunnel assessments.

(ii) To extend the method to the assessment of platform tunnels, concourses and deep level passages.

(iii) To extend the method to the assessment of shafts, including escalators.

(iv) To conclude, explaining how the proposed method adequately meets the requirement of LUL Standard E3322 A2 Deep Tunnels and Shafts Assessment′and Schedule 3 of the PPP Contract.

3. Running Tunnels

On the Northern and Piccadilly lines the vast majority of tunnels are of bolted cast iron construction, run alongside each other at varying separations, and are built within the London Clay strata. Although the soil strata in London have a considerable amount of variability (2), conservative properties can be generically assigned to the strata and "first assessments" can be made using the elastic continuum method (using TOTALINE (3)), for which the only significant variables are the depth below the ground, and the elastic modulus of the strata at tunnel level (which also varies with depth).

A generic assessment can be carried out for the majority of cast iron twin running tunnels in London Clay. This generic assessment is supported by numerical analyses carried out by Geotechnical Consulting Group (4). Similar generic assessments can be made for articulated concrete tunnels in London Clay. The exceptions to these generic assessments will be sections of tunnel which are damaged in some way, deformed beyond a limiting value of 1%, or have a special form of construction, like "piggyback", a cross passage opening, pump sump, or shield chamber. Figure 1 illustrates a section of tunnel and the features as described that can be identified.

The management of these exceptions is described in the flowchart shown in Figure 2 The assessment of standard′undamaged running tunnels is represented in the centre track of this chart, initially in blue, then in hatched green after an assessed pass at the first assessment stage. The first assessment of this category makes implicit assumptions about tunnel geometry, tunnel strength and soil conditions. These assumptions are thought to give a conservative assessment. Work then needs to be carried out on site for this hatched green category to confirm, so far as is reasonably practicable, that the assumptions made in the first assessment are in fact conservative. This investigation work will take the form of circularity checks, non-destructive testing, coring and material testing. If the outcome of these tests is satisfactory a final report will confirm this and the tunnel will be categorised as Condition A′, or condition B if there are non-structural concerns such as encrustation or seepage.

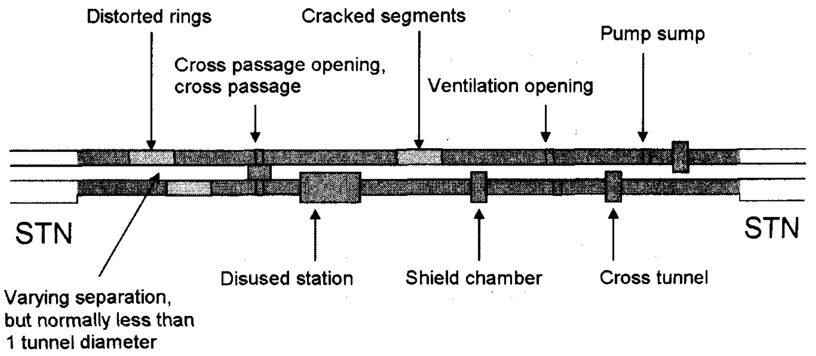

Figure 1 A Typical Tunnel Length

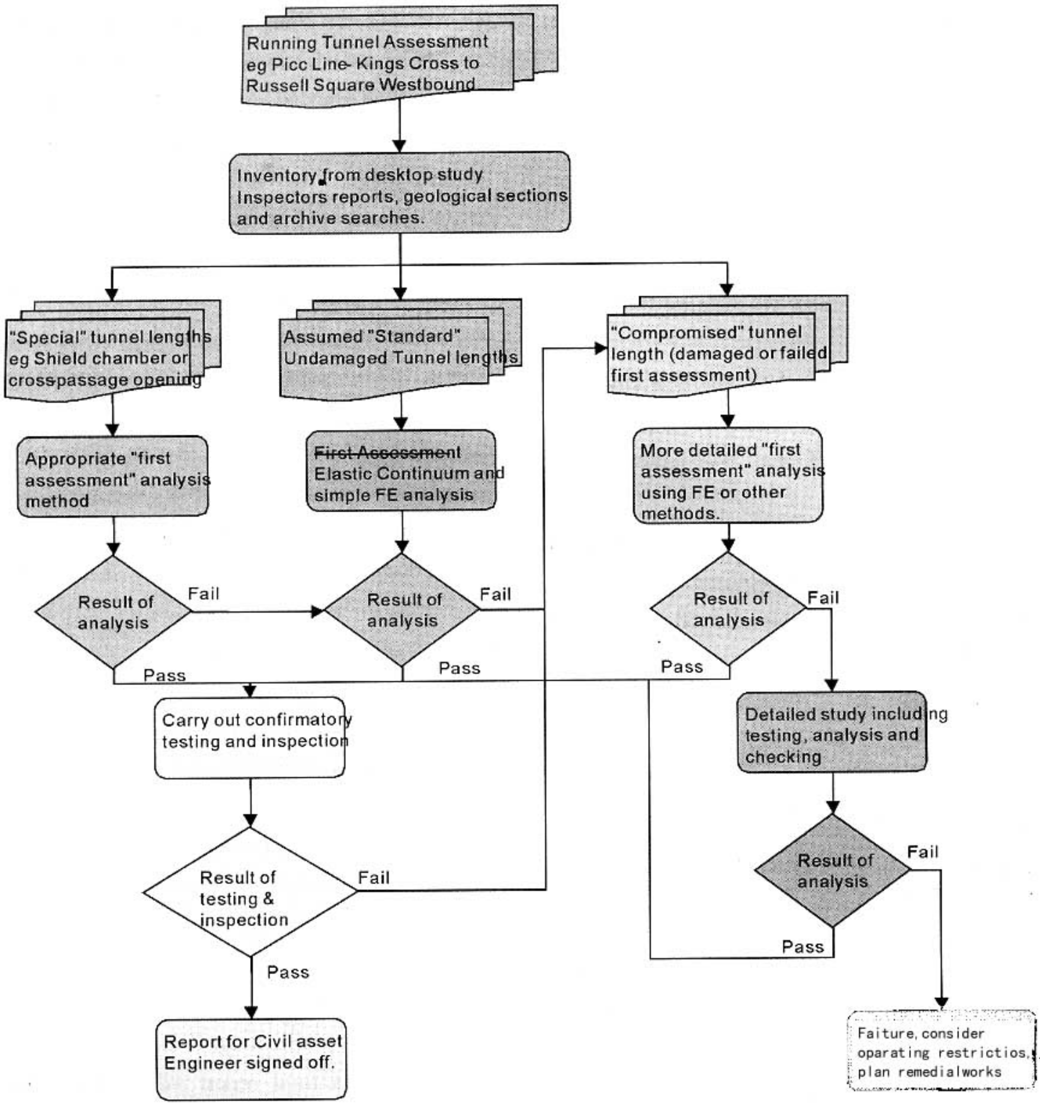

Figure 2 Flowchart Describing Running Tunnel Assessment

For standard tunnel lengths that are damaged, distorted more than 1% of diameter, or have failed their first assessment, termed compromised′, they follow the orange track on the right, and undergo a more detailed analysis, including a finite element analysis, if appropriate. If they pass the more detailed analysis they join the hatched green category and provisionally go into Condition Category B′. If they finally fail the assessment they go to Condition Category D/E′, and undergo a final more detailed investigation, including material testing if necessary, to determine whether they are safe or unsafe. If they are then judged to be unsafe they would go to Condition Category E′and Tube Lines would have to carry out appropriate monitoring or remedial work in accordance with the PPP Contract; otherwise they remain in Condition Category D′with, perhaps, an appropriate monitoring and/or inspection regime put in place.

For specials′ an appropriate assessment method would be selected and an assessment carried out. The assessment may be generic, as in the case of 2 – plate cross passage openings of similar construction, for example. If passed, these specials′ go into the hatched green category, for confirmatory checks, and go into

Condition Category A' or B'. If failed, they join the orange compromised' tunnels and undergo further detailed testing.

4. Station Tunnels

Station tunnels are generally more complex than the running tunnels and shafts, and are generally evident to the general public and station staff. However the structural fabric is usually obscured by finishes. In order to assess these station tunnels it is proposed to take broadly the same approach as running tunnels (see Figure 3.2).

Platform tunnels are of particular importance, as they house the operational railway as well as the public, and are of a large diameter containing a number of openings. These tunnels usually utilise "rolled" rings, in which the longitudinal joints are staggered, and this makes the tunnel a stiffer structure.

Platform tunnels may be assessed generically if appropriate, but where they have a large number of openings they will be regarded as specials. The elastic continuum method can be utilised to some extent, but the proximity of adjacent structures makes it more likely that detailed numerical methods will play a part.

Checking by established geotechnical and tunnel experts will form an essential part of the assurance process for this work. There will be few damaged linings that are visible, as all damage will be obscured by finishes. Unless the structural fabric is revealed temporarily as part of station modernisation, it will have to be assumed that the fabric is intact, but the confirmatory checks, using NDT and BEM methods, as well as circularity checks and coring where possible, will need to be more comprehensive than for the running tunnels, where most faults are apparent from the inspectors reports and other condition - based surveys. Circularity surveys will be complicated by the need to carry out covermeter surveys in order to determine the depth of structure beneath the station finishes, and so obtain the circularity of the structural linings themselves rather than the finishes. Coring may require the removal of finishes by a contractor before the coring is carried out. A good quality temporary repair will have to be immediately made, and a final repair agreed and expedited as soon as possible to avoid any reduction in station ambience.

For concourses and other passenger connections, it may be possible to carry out generic analyses, and confirm the form of construction using ultrasonics or simply a covermeter. As before there will be orange and grey categories here also.

5. Shafts

Analysis of vertical shafts is potentially a simpler exercise than tunnels, as soil loads tend to be concentric. Nominal out - of - balance loads from uneven grouting or ground anomalies will need to be derived. Orange and grey categories will be assessed also. Included in this category will be cable and vent shafts, some of which, paradoxically, are actually horizontal (tunnels). Shaft cover slabs will be assessed by the Structures team, but masonry shaft tops and base slabs will have to be assessed as part of the Tunnel Assessments Project.

Escalator shafts will be more difficult, being inclined, and housing sensitive machinery. Mostly the fabric of escalator shafts is obscured, although it is usually possible to see the structure in the invert and sides, beneath the escalator.

6. Site Testing and Investigation

Running Tunnels

For standard' undamaged running tunnels, it needs to be established that.

(a) The tunnels are less than 1% out - of - circular.

(b) Lining thicknesses are as assumed.

(c) Soil and drainage conditions are at least as assumed.

(d) Lining stresses are as assumed.

(e) Lining material strength is as assumed.

For (a) a fairly complete circularity survey of the running tunnels needs to be carried out, with measurements at least every 5m. For (b) sample coring or NDT would be appropriate. For (c) some soil sampling outside the tunnel needs to be carried out. For (d) an overcoring or NDT method could be used. For (e) the material extracted from a core could be tested.

For compromised' tunnel sections more focussed checks of types (a) to (d) will be carried out, where considered necessary. Special´ running tunnel sections may require a fairly simple structural assessment (like standard´running tunnels) but could require more demanding analysis and testing (as compromised´) where appropriate.

Station Tunnels

For platform tunnels it will be much more difficult to carry out the same sort of tests as for running tunnels, because of the presence of finishes. It may be possible to carry out circularities, using a combination of laser measurement and Broadband Electromagnetic (BEM) survey. BEM can also be used to determine lining thickness through station finishes.

Determination of lining stresses and physical measurement of thickness by overcoring would require the removal and repair of station finishes. This may be possible, but will tend to reduce the number of cases for which this work could be carried out. Alternatively the assessment work should be designed to fit in with station modernisation work i. e. looking in detail at the tunnel structures once the finishes have been removed. In addition, carrying out such testing and investigation work in disused station tunnels may help to validate generic assessment of all station tunnels.

Shafts

The structural fabric of vertical shafts is generally exposed, so similar tests to running tunnels can be carried out for verification purposes.

Escalator shafts will be much more difficult as access is extremely restricted beneath the escalator, and station finishes would have to be removed for any investigation above the escalator. In addition access over the escalator can only be accomplished by falsework set on the escalator itself, for which the loading is limited. Nevertheless it is possible that it may be necessary to carry out investigation work on escalators.

7. Phasing

Table 1 explains the proposed phasing of the Tunnel Assessments.

Stage 1 is the current desktop study, represented in blue on the flowchart in Figure 3.2, and encompasses inventory and definition as*standard´*,*compromised´* or*special´*, as well as first assessment of*standard´* tunnels and shafts.

Stage 2, which starts in September 2003, and will continue for 18 months, encompasses first assessment of*special´* and*compromised´* tunnels and shafts, validation of the assessment methods, confirmatory site testing for*pilot* ´tunnels and shafts (about 10% of the total), and final assessment reporting for*pilot´* tunnels and shafts.

The final stage, Stage 3, will continue for a further three years, and will include any detailed studies on*special´* and*compromised´* tunnels and shafts that have already failed their first assessment, and reduced – scope confirmatory testing and final assessment for all remaining assets.

Table 1 Stages of Assessment

STAGE 1 Mar 03 – Sep 03	STAGE 2 Oct 03 – Mar 05	STAGE 3 Apr 05 – Dec 08
Inventory by desktop study.	First Assessment for *special´* and *compromised´* tunnels and shafts.	Detailed studies as required.
Tunnels & shafts defined as*standard´*,*compromised´* and*special´*	Validation for Assessment Process	Confirmatory testing for all assets (excluding those which formed part of the*pilot´* phase).
First assessment of*standard´* tunnels & shafts.	On – site verification for*pilot´* tunnels & shafts. (Approximately 10 %)	Final assessments of*pilot´* tunnels & shafts.
Standard´ tunnels and shafts that fail first assessment now classed as" *compromised*".	Final assessments for remaining tunnels & shafts.	

8. Conclusions

This document sets out the proposed process for assessing all Tube Lines deep tunnel and shaft assets in accordance with LUL Standards and the PPP Contract.

It should be pointed out that the relevant LUL Standards and the PPP Contract do not stipulate exactly how tunnel and shaft assessments are to be carried out. There is a great deal of scope for interpretation of these documents. The guiding principle in making this interpretation has been to carry out assessments at the least possible cost and effort, but to do sufficient analysis, testing and verification to satisfy Tube Lines professional tunnel engineers, and in turn to convince LUL and Tube Lines Asset Engineers that the assessments reduce the risk to the operational railway to an ALARP level.

Appendix B

An Outline History of London Underground.

1843 Opening of the Thames Tunnel constructed by the Brunels. It was purchased by the East London Railway Company in 1865 for £ 200000. The first trains ran through it in 1869 and it is now part of the East London Line. It is brick lined.

1863 The Metropolitan Railway opened the World's first underground railway on 10 January provided link between Main Line Stations and the City. 6km long. Cut and cover brick lined with brick arched or canopy roofs in the stations.

1868 The Metropolitan District Railway opened between South Kensington And Westminster. This is now part of the District & Circle Lines..

1870 The first Tube tunnel from the Tower to Bermondsey. First used by Cable - cars then pedestrians; closed when Tower Bridge opened in 1894.

1884 Completion of what is now the Circle Line

1890 The City and South London Railway opened the first deep level electric railway from King William St (City) under the Thames to Stockwell.

1898 Opening of the Waterloo and City Line "The Drain" (this was not formally incorporated into London Underground until 1994.

1900 Opening by HRH the Prince of Wales of the "Twopenny tube" from Shepherd's Bush to the Bank. It is now part of the Central Line.

1902 Underground Electric Railway Company of London (The Underground Group). Joined all lines together except the Metropolitan by 1914.

1905 District and Circle lines electrified.

1906 Baker Street and Waterloo Railway from Baker Street to Kennington Road (now part of the Bakerloo Line).

Great Northern, Piccadilly and Brompton Railway opened between Hammersmith and Finsbury Park. This is now part of the Piccadilly Line.

1907 Charing Cross, Euston and Hampstead Railway from Charing Cross to Golders Green and Highgate (now Archway) opened. Now part of Northern Line.

Albert Stanley (later Lord Ashfield) appointed General Manager of the Underground Electric Railway Company of London Ltd.

1908 Adoption of the name "Underground"

Electric ticketing machines introduced.

1911 First escalators introduced (at Earl's Court)

1913 The famous Logo first Appeared.

1923 Central overhaul depot opened at Acton.

1929 Last manually operated doors replaced by mechanical.

1933 The Harry Beck Underground map introduced.

1933 London Passenger Transport Board - The Metropolitan Railway, The Underground Group and 170 railway, tram, trolleybus, and coach companies in London area.

1940 From September tube stations used as air - raid shelters until May 1945. The Aldwych branch was used to store treasures from the British Museum and remained closed until 1946.

1948 London Passenger Transport Board officially Nationalised becomes the London Transport Executive, part of the British Transport Commission which also controlled British Railways, Docks, Canals, Airlines, and Road Freight.

1952 The first Aluminium train introduced.

1955 Programme machine signalling introduced at

Camden Town.

1961 End of steam and electric locomotive haulage of London Transport passenger Trains.

1962 First experiments in automatic train operation on the District Line between Stamford Brook and Ravenscourt Park.

1963 The London Transport Executive became the London Transport Board and reported directly to the Minister of Transport.

1968 - 9 The Victoria Line opened in stages.

1970 The Underground and Greater London area bus network passed to the The London Transport Executive and reported to the now extinct Greater London Council.

1971 Last steam shunting and freight locomotive removed from service.
Victoria Line Extended to Brixton.

1975 New safety measures introduced following fatal accident (43 killed) at Moorgate.

1977 Opening of Heathrow Central by HM Queen Elizabeth II.

1979 Opening of Jubilee Line by Prince Charles

1983 Dot matrix indicators introduced on platforms.

1984 London Regional Transport (LRT) created, reporting to the Secretary of State for Transport.
The London Regional Transport Act contained provision for setting up subsidiary companies to run the Underground and bus services.
Hammersmith &City and Circle Lines trains converted to one person operation

1985 Incorporation of London Underground Limited a wholly owned subsidiary of LRT.

1986 Piccadilly line Terminal 4 extension.

1987 Tragic fire at King's Cross killed 31 people.
New self - service ticket machines introduced throughout the network.

1988 Individual business units created to manage the Underground lines
New passenger security measure trials before system - wide adoption
Go - ahead for £ 555 million Central Line Modernisation including new trains and signalling.

1989 Fire Regulations (Sub - surface Railway Stations) introduced following Fennell Report into King's Cross Fire.

1992 London Underground Customer Charter launched

1993 £ 70 million Angel Station reconstruction completed
Work started on £ 2. 6 billion (estimated!!) Jubilee Line Extension from Green Park to Stratford.

1994 Penalty Fares introduced.
London underground took over Waterloo & City Line and responsibility for the Stations on District line from Putney Bridge to Wimbledon Park.
Aldwych Station and the Central LLine branch from Epping to Ongar closed.

1998 20March1998 John Prescott Government plans for Public Private Partnership (PPP) to

- Keep a single unified body in the Public Sector for operating London Underground.
- To utilise the Private Sector's finance and construction capacity in a PPP to overcome the investment backlog and to award one or more contracts to maintain and modernise the Underground's infrastructure, under which the Private Sector will raise the substantial sums needed for investment.

2000 Transport for London TfL put all London's transport "under one hat" The Mayor of London's.

2003 Following period of "Shadow Running" from 1998 - 2003 PPP was finally introduced as follows:

- Public Sector operating company London Underground Limited.
- Three Private Sector Groups

Tube Lines (responsible primarily for the Jubilee, Northern, and Piccadilly Lines, & Docklands Light Railway).

Metronet BCV (responsible for the Bakerloo, Central & Victoria Lines)

Metronet SSL (responsible for the "Sub - Surface Lines" primarily those that link up with main line railway routes The Metropolitan, District, Circle, Hammersmith & City)

2003 15 July London Underground officially came under Transport for London TfL control.