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Managing Technical and Operational Change: How understanding a railway's historic evolution can guide future development: A London Underground case study.

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Abstract

The argument for this thesis is that patterns of past engineering and operational development can be used to support the creation of a good, robust strategy for future development and that, in order to achieve this, a corporate understanding of the history of the engineering, operational and organisational changes in the business is essential for any evolving railway undertaking.

It has been the objective of the author of this study to determine whether it is essential that the history and development of a railway undertaking be known and understood by its management and staff in order for the railway to function in an efficient manner and for it to be able to develop robust and appropriate improvement strategies in a cost-effective manner. The above argument was advanced because of various widely published and well-known problems in the industry where projects have failed to be completed, where there have been long and unnecessary delays to work or production or where accidents and incidents were caused by a lack of experience, knowledge or understanding of staff.

In this thesis, it is shown that a railway is a complicated and complex system, being an entity that combines staff and a fixed infrastructure and moving components and equipment, all of which are expensive to install, operate and maintain. Since the operational life of much of the hardware is greater than the time employees spend in service on the railway, it is common for the origins and reasons for systems developed and / or installed on the railway to be forgotten. Knowledge of the reasons for retaining or changing processes and systems can be lost when staff retire or leave the employment of the railway and newcomers rarely appreciate the background and purpose of some of the systems still in place when they join the organisation. Generally, little attention is paid to history and development during training; indeed, such knowledge may not even be considered necessary or relevant.

The writer of this thesis uses London Underground as a case study to show how the engineering and operational development of the system has impacted on the design of rolling stock. The objective of the work is to show how the development needs arose, how they were addressed, what were the outcomes and what lessons were (or were not) learnt as a result. The rate of progress is discussed, as are the reasons for that rate. There are also suggestions for the reasoning behind the evolution and how these led to the specific solutions. The author offers suggestions as to the way in which development might be managed in the future and what the risks might be. He suggests that, in systems engineering terms, railways must generate rich requirements and use rich traceability in order to establish a process of learning from history that is not entirely dependent on knowledge being retained and long serving staff. It should be noted that this is not a historiographical study and, whilst it draws upon academic literature on corporate memory loss, it is also not intended as a contribution in this field.

The author of the thesis concludes that it is essential for railway engineering and operations managers to understand the way in which technical systems and operational arrangements have evolved on a railway during its history, both as a result of conscious decisions and happenstance. The case study shows how its development history has shaped the current London Underground system and is still shaping it today. In fact, the author proposes that the railway is vitally dependent on an understanding of its past if it is to succeed in obtaining the most cost-effective and stakeholder-friendly solutions for its ongoing development.

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Glossary of Terms / List of Abbreviations

Term	**Explanation / Meaning / Definition**
A	Ampere, Unit of Current
AC	Alternating Current
AEG	Allgemeine Elektricitäts-Gesellschaft - the German company that had the early licences for the sale of Thomas Edison's products in Germany.
ATC	Automatic Train Control
AWS	Automatic Warning System - magnetically activated railway signal status indication system for trains
BIM	Business Information Modelling
BR	British Rail – the pre-1994 nationalised railway organisation in Britain.
BTH	British Thomson-Houston - the British arm of the American General Electric Company (GE, q.v.) that supplied the bulk of the Underground's electric traction equipment until the 1980s.
BW	The British Westinghouse Electric and Manufacturing Company – A company originally set up in Britain in 1899 to sell American designed Westinghouse electrical products in Britain. Later became Metropolitan Vickers (q.v.)
C&SLR	City & South London Railway - the company that owned the first electrically operated tube railway in London, which eventually ran from Clapham Common to Euston via the City. It is now the City branch of the Northern line.
CLR	The Central London Railway company, opened in 1900 between Shepherds Bush and Bank and later extended to Liverpool Street and Ealing Broadway. Became the core part of the Central Line.
CSDE	Correct Side Door Enable – introduced after One Person Operation (OPO, q.v.) to prevent errors in platform side door opening.
CT	Control Trailer car - vehicle with a driving cab but no traction power equipment
CTBC	Combined Traction/Brake Controller
DC	Direct Current
DM	Driving Motor car
DfT	Department for Transport
DT	Driving Trailer – alternative name for a control trailer, i.e., a vehicle with a cab but no traction power equipment.
DTP	Deep Tube Programme

Term	Explanation / Meaning / Definition
ECEB	Electrical Control of Emergency Braking – introduced for the 1973 Tube Stock to replace the Westinghouse brake as the on-board safety brake system.
E.P. (B.)	Electro-Pneumatic (Brakes/Braking)
FA	Fault Annunciator – electronic system first introduced on 1973 Tube Stock.
GB	Great Britain (England, Scotland and Wales)
GE	General Electric – The American company, originally founded by Thomas Edison, which was reformed when Edison's company was absorbed by the Thomson-Houston company.
GEC	General Electric Company – The British company founded in 1886 that first supplied the Underground with electric traction equipment only in 1923.
GNPB	Great Northern, Piccadilly & Brompton Railway - the official company title of the Piccadilly Line 1906-1910.
GTO	Gate Turn Off (thyristor) - used in 1990s traction power circuits for DC motor control. Also used on mainline railways for AC power control.
GWR	Great Western Railway
h.p.	Horsepower, a unit for power. 1 h.p. = 764 W
HSCB	High Speed Circuit Breaker.
IEP	Intercity Express Project – the replacement train for the high-speed diesel train.
IGBT	Insulated Gate Bipolar Transistor - now a common component in electric traction power circuits. Replaced thyristors and GTOs.
LER	London Electric Railway - A company formed in 1910 by amalgamation of the Baker Street & Waterloo Railway (the Bakerloo line), the Charing Cross, Euston & Hampstead Railway (the Hampstead line) and the Great Northern, Piccadilly & Brompton Railway (the Piccadilly line).
LTE	London Transport Executive, 1948-1962. Replaced the LPTB (q.v.).
LNWR	London & North Western Railway - The name of the company that owned (amongst other routes) the West Coast main line route from London Euston to Watford, Birmingham and northwards to Carlisle.
LPTB	London Passenger Transport Board, 1933-1948 - the statutory organisation set up to take over London's underground railways and bus companies in 1933.
LT	London Transport - the brand name for London's public transport services between 1933 and 2000 when it was replaced by Transport for London (TfL, q.v.).
LTB	London Transport Board, 1963-1970. Replaced the LTE (q.v.).
LTM	London Transport Museum

Term	Explanation / Meaning / Definition
LU	London Underground
M	Motor car
MA	Motor Alternator
MAR	Motor Alternator Rectifier
Met. Rly.	Metropolitan Railway – the original owning company of most of today’s Metropolitan line.
MDR	Metropolitan District Railway - the original owing company of today’s District line.
MG	Motor Generator
MM	Middle Motor car (only used on the District).
MTR	Mass Transit Railway Hong Kong (the heavy metro serving Hong Kong)
MTRCL	Mass Transit Railway Corporation Limited of Hong Kong.
MU	Multiple Unit - A train using a system for controlling distributed power and other equipment from a single driving or control position.
MV	Metropolitan-Vickers - A company formed from the original British Westinghouse company and Vickers that supplied electrical equipment to the Underground.
NDM	Non Driving Motor (car)
NAO	National Audit Office
NR	Network Rail
NTfL	New Tube for London - The design proposals for new tube rolling stock published by TfL in October 2014.
OMO	One Man Operation - used until replaced by the more politically correct OPO.
OPO	One Person Operation - first introduced in 1984 to reduce train crew from two to one person.
PEA	Passenger Emergency Alarm
psi	Pounds per square inch - a measure of pressure. 14.5 psi = 1 bar.
PPP	Public Private Partnership.
RoSCo	Rolling Stock (leasing) Company, as set up under British railway privatisation in the mid 1990s.
SAPB	Spring Applied Parking Brake - an automatic parking brake used on Underground trains built from the late 1970s.
SCAT	Speed Control After Tripping

Term	Explanation / Meaning / Definition
SSL	The sub surface lines of London Underground, marketed as the Metropolitan, Circle, Hammersmith & City and District lines.
T	Trailer car
TCIC	Trip Cock Isolating Cock
TEP	Train Equipment Panel - Successor to the FA (q.v.) on the 1973 Tube Stock.
TfL	Transport for London - the current public sector owners of the London Underground system.
TOC	Train Operating Company - for a main line railway operating franchise.
TPWS	Train Protection & Warning System - audio frequency based intermittent automatic train protection system installed on most British main line railways.
UERL	The Underground Electric Railways of London Ltd. - the holding company set up in 1902 to finance the electrification of the District Railway and the completion of the Bakerloo, Piccadilly and Hampstead tube railways then under construction. It became known as 'the Underground Group" and it later absorbed some London bus and tram operations. Also known internally as 'the Combine'.
UK	United Kingdom (Great Britain and Northern Ireland)
V	Volt, unit of voltage.
W&C	Waterloo & City Railway - built by the London & South Western Railway as a tube connection between its main London station and the City. Opened in 1898 and absorbed into London Underground on 1st April 1994.
WCML	West Coast Main Line
WJS	Watford Joint Stock - a Tube stock fleet partially owned by the LNWR and partly by the LER. It was delivered in 1920 to work the Bakerloo service to Watford over the 'New Lines' built adjacent to the LNWR main line out of Euston.

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1 Introduction

1.1 Background

This thesis originates in the author's observation over more than 20 years that there have been regular instances of serious project failures in the railway industry, due to inadequately competent management. The study therefore looks to the past to find why in recent decades mature organisations like Network Rail and London Underground (LU) have tried to introduce inappropriately radical technologies, with the consequence that major projects have overrun in time and cost. These historical insights are then used to suggest ways in which future projects can be better developed, planned and implemented.

The focus is on LU because, as a former employee, the author has a deep knowledge of that railway's engineering development. Many years ago, he noted a long-standing pattern: many standards and methods adopted in the early 20th century were still considered fit for purpose in the 21st century. Indeed, through what we should now call incremental development and recycling, very old and technically outdated equipment was still being successfully used. He thus wanted to find out if the knowledge of this combination of technological change and stasis might help present-day engineers and managers come to a better understanding of railway systems, form better strategies for future enhancements, and thus aid effective planning for project development and management.

The writer of this thesis argues that observed patterns of historical engineering and operational development do indeed have the potential to suggest robust strategies for future technological development on LU and other railways. The successful evolution of railway engineering systems will depend on railway managers developing training and knowhow preservation programmes that ensure that historical knowledge is never lost at the corporate level and is always passed on to current and future generations of engineers and engineering managers.

1.2 Context

A railway is a transport system that uses a fixed guideway on or in a purpose-built civil engineering structure and that is designed to carry passengers and/or freight in trains of specially designed coaches or wagons. As an integrated system, the railway requires constituents with a high level of engineering and operational integrity in order to provide a reliable and safe service for its customers. This high level of integrity is achieved only if the design, procurement, installation, control and maintenance of the system are carried out by companies and personnel with the right level of education, training, expertise and experience. The railway also requires the support of society, government and local authorities. All this creates a diverse set of stakeholders.

The railway system is made up of a number of diverse subsystems and components, each of which has an interface and interactions with one or more of the other subsystems and components. In broad engineering terms, the main constituents of a railway are civil engineering structures, mechanical, electrical and electronic engineering elements (for power supply, traction and signalling control purposes), telecommunications equipment, data management and building management systems, as well as emergency and evacuation systems. Each of these main constituents contains several more subsystems that, equally, must interface with each other within their own host and often, with other main components.

The complexity of the railway system and its need for high integrity engineering leads to high construction and equipment costs but these are mitigated to some extent by many of the assets having a long life. Thus, civil engineering structures may last for 100 years and longer, buildings for 60 years or more and rolling stock for 40 years or more. This longevity results in a need for good asset management and for a thorough understanding of the original concepts for and subsequent changes to the assets and to their operation. In the past, there had been a culture of career-long service for staff within the railways which aided the development and retention of experience over long periods. Almost fortuitously, this resulted in a body of tacit corporate knowledge that allowed an informed management of assets and their replacement. Such life-long commitment to a single industry has ceased to be common and, thus, corporate knowledge is no longer created by default.

In Britain, there are two principal railway networks, namely, the main line system managed by Network Rail as an arm of the Department for Transport (DfT) and the London Underground (LU), managed within Transport for London (TfL). When the main line railways were de-nationalised in the mid-1990s, what had been a holistic system was fragmented and train service operators were separated from infrastructure managers. Mainline operations were broken up into separate commercial franchises while the infrastructure manager acted as the railway system’s landlord. As a result, there were many changes to management and personnel across all disciplines within the business and many experienced staff left the industry or took on new roles that did not align with their experience. A similar loss of tacit corporate knowledge befell London Underground because of the failed Public Private Partnerships (PPPs) and subsequent reorganisations, aimed at reducing the cost base of the organisation.

In addition to the loss of experienced personnel on the railways over the past 20 years, there has been a shift in employment expectations, as mentioned above, away from long service with one company towards employees spending relatively short periods in one job in an industry or with a single company. This has led to much movement of staff into and out of the railway industry and between companies within the industry. The apparent result has been a loss of corporate knowledge and experience and this may have contributed to some major project failures (Elliott, 2014).

Even day to day operations have come in for regular criticism. Chris Green, a well-known, long serving, professional railwayman and former chief executive of Virgin Trains, quoted by Strangleman, said: “The collapse in professional delivery has been the biggest surprise in rail privatisation. Simple things that railway people once did without thinking have now become a major crisis.” (Strangleman, 2004, p. 164). In this statement, Green expresses a perception commonly held amongst experienced and long-serving railway professionals in Britain that, since privatisation, the quality of railway management has been diluted by the influx of a new breed of ‘business managers’ most of whom have no railway experience or training (Strangleman, 2004 pp. 164-167). As a result, simple mistakes are being made that have caused and still cause serious problems for railway system performance and that, in some cases, have led to the deaths of passengers or staff, e.g., in the Hatfield accident of 17 October 2000 (ORR, 2006) and the Grayrigg derailment of 27 February 2007 (RAIB, 2011). Whilst the views of Green and others might be viewed as confirmed by incidents like Hatfield, in reality, it is likely that there were other forces at work that were equally or similarly to blame, e.g., commercial priorities in the case of Hatfield and increased service levels in the case of Grayrigg. What is widely held, however, is that existing corporate or tacit knowledge is often seen by new or incoming management as ‘old railway’ or ‘not the way we are going to do things now’ and, as a result, it is ignored or allowed to fade away, only to be found to be essential again shortly thereafter (Strangleman, 2004, p 144 et seq.).

1.3 Project Failures and their Consequences

This section briefly reviews some of the more egregious project failures of the last thirty years, where it is plausible that a loss of corporate memory was at least partly responsible.

1.3.1 Mainline Example 1: WCML Modernisation

In comparatively modern history, the West Coast Main Line (WCML) upgrade project is perhaps the worst example of railway management failings arising from a lack of experience, knowledge and knowhow that resulted in a lack of control. The upgrade had its roots in a pre-privatisation understanding that the line, running between London (Euston) and Glasgow and electrified in stages between 1966 and 1972, was in urgent need of rehabilitation and greater capacity. Much of the infrastructure was approaching 30 years in age and, for many years, insufficient funding had been provided to allow adequate maintenance (Butcher, 2010). Privatisation of the railways in the mid-1990s had led to the formation of Railtrack in 1994 and this organisation took over responsibility for the WCML modernisation. In their first appraisal of the upgrade needed to provide replacement of the power supply, track improvements and new signalling of the ‘moving block’ type, Railtrack proposed, in 1997, an initial budget of £750million (Butcher, 2010). The planned adoption of the ‘moving block’ train control system had been promoted by a senior engineer who expected cost savings and a significant increase in capacity by doing away with lineside signals.

In 1998, an agreement was reached between Railtrack and the Virgin Rail Group (VRG), who operated the privatised West Coast passenger franchise. It included the introduction of the new signalling and new trains running at 140 miles per hour (the Pendolinos). The budget was now set at £2.5billion, a demonstration that the £750million of the previous year had been seriously underestimated. By 2001, it was obvious that neither the infrastructure modernisation nor the new trains would be ready for delivery in 2002 as set out in the agreement (NAO, 2006). Interestingly, VRG, managed by experienced railway staff, had insisted on a very high level of damages when it agreed to the upgrade contract with Railtrack.

Alongside the totally inadequate management of the aftermath of the Hatfield accident, also caused by a lack of expertise, Railtrack’s failings in this project played a significant part in the government’s decision to force the organisation into administration in October 2001. At this point, cost estimates had risen to more than £10 billion and the project was two years behind schedule (Crompton and Juke, 2007). By May 2002, Railtrack’s projection of the programme’s final cost had risen from £2.5 billion to £14.5 billion, with the first stage of implementation due in May 2006. The scheme for moving block signalling had been dropped by now, but it had already cost £350 million. Eventually, upon completion of a substantial part of the project in December 2008, the final cost was stated to be £8.8billion but another £1billion of electrification works was needed to complete the power upgrade (Butcher, 2010).

The project governance of the WCML upgrade had failed because there was little engineering expertise at board level, the company had believed in outsourcing everything, including technical advice, and its project management capacity proved inadequate for dealing with the additional interfaces caused by the need to co-ordinate multiple levels of consultants, contractors and subcontractors. Another element was the need to make compensation payments to TOCs. By the end of its existence, Railtrack projects were costing two to three times as much in real terms as BR had paid. Even today, in 2017, the lack of railway experience and knowledge which caused this collapse has not yet been properly overcome.

1.3.2 Mainline Example 2: GWR Main Line Electrification

In 2009, the UK Department for Transport announced that the Great Western main line (GWML) would be electrified between London and Cardiff and that this and other routes would be operated by a combination of electric and bi-mode high speed trains. The original cost for the electrification of the route was widely reported as £874 million. By 2016, this had risen to £2.1 billion (NAO, 2016, p. 4). A wide range of reasons for the increase were listed in the NAO report (2016) and can be summarised as follows:

- Lack of integrated planning by the DfT;
- The Network Rail schedule was unrealistic;
- Absence of allowances for planning permissions;
- The decision to redesign the overhead line system;
- Lack of bottom up estimating of costs;
- Lack of integration for new technology, (NAO, 2016).

In this example of management failings, the absence of the correct type of expertise at middle and upper management levels and the lack of engineers and planners with sufficient experience was given as the main reason for the huge increases in costs, an extension of the project's duration by several years and curtailment of the extension of electrification from Cardiff to Swansea.

The failings of the GWR electrification have caused a significant change in government policy: in July 2017, it was decided to use bi-mode trains over many miles of route that would no longer be electrified. Thus, managerial failings led to the abandonment by the UK government of their electrification policy in favour of diesel traction. This cannot be acceptable in an era when there is a world-wide commitment to the reduction in fossil fuels and it is essential that lessons are learned from the history of projects like this.

Although London Underground (LU) was not moved out of state management at the same time as the main line railways, a Public Private Partnership (PPP) engineering and maintenance contracting arrangement was introduced in stages from the late 1990s and the resulting changes to management and the effects on personnel and on the LU system were very similar to those experienced on the mainline network. The PPP system collapsed in 2008 and, since then, LU has brought its engineering back in house. Two specific examples of LU project failure are introduced here.

1.3.3 London Underground Example 1: Jubilee Line Extension

In February 1990, after several years of political and financial manoeuvring, work was started on the extension of the London Underground Jubilee line from Green Park to Stratford, involving 16 km of new railway construction, mostly in deep level tube tunnels, new stations, new trains and a new train control system. The story of the extension and its construction are ably described in the book, ‘Jubilee Line extension, from concept to completion’, by Bob Mitchell (2003) so it will suffice here for the author to reveal that he was involved with the project and the later issues resulting from it.

The project started well, according to Ove Arup, (cited in Allsop et al. 2008) with a budget of £2.1 billion and a timescale of 53 months but it ended after 74 months in December 1999, having cost £3.5 billion. The problems were largely related to the mechanical and electrical installations and, in particular, to the integration of the new signalling intended for the line with other technical systems.

The LU engineering director of the time insisted that the whole line should be equipped with ‘moving block’ signalling, at that time an untried and untested system, which was to rely on radio transmission of movement authorities and train based navigation and positioning. The proposal was aimed at a 100 second headway at peak times, something the Underground had wanted to do but had not achieved successfully with modern train control techniques[1]. Westinghouse Signals Ltd. had persuaded the engineering director that they could develop and deliver such a system and the author recalls heated conversations with him as to the wisdom of trying the system without “testing it in anger somewhere first”, whether it would offer the projected benefits and how it would be accepted by London Underground’s own signalling engineers from a safety perspective. Had the memory of the extensive pre-service testing carried out in the mid-1960s, during the development of the Victoria line ATC system, been retained, a more rational approach might have prevailed and much money saved.

Eventually, Westinghouse admitted that they were struggling with the technology and would not be able to deliver it in time for the line’s planned opening in December 1999. A major contributing factor in this failure was the integration of more subsystems into the scope of the train control system than originally planned. Westinghouse provided a fall-back, fixed block system which gave a 212s headway or

[1] An 82 second headway was regularly timetabled on some lines using fixed block signalling in the 1950s and earlier but was rarely achieved, the service at the end of the peaks invariably, in the author’s experience, running 5-10 minutes late.

17 trains per hour instead of the proposed 36 trains per hour.

The 67% overrun in costs and the project delays were widely reported as contributing to the governmental view that LU's management was incompetent (Wolmar, 2002) and it was said that this led to the imposition of the now collapsed Public Private Partnership (PPP) that handed the maintenance and rehabilitation of the Underground's infrastructure and equipment, including rolling stock and signalling to the private sector.

Ove Arup acted as Agent to the Secretary of State for Transport on the project. Their review of the project management of the JLE project was damning, declaring that London Underground Limited had failed to apply the proper level of robust and effective guidance to the JLE project. Arup's End-of-Commission Report stated: "a client who does not have the experience, resources and capability to direct his project manager on a large, complex multi-disciplinary development needs to appoint a senior Board member to be responsible for the project. The board member should be supported and advised by a group whose members will be experienced in programme, progress and cost disciplines and have the authority of the Board to monitor, probe and challenge the project manager on detail and implementation." (Arup, 2000, p15). The author agrees wholeheartedly with this assessment.

It is worthy of note that the senior engineer who had espoused the moving block concept for the Jubilee line had moved from London Underground to Railtrack in 1995 and, as related above (1.3.1), attempted to impose the technology on the West Coast Main Line as part of its upgrade programme.

1.3.4 London Underground Example 2: Sub Surface Lines Resignalling

The sub surfaces routes operate on the oldest part of London Underground's network. In August 2015, after 12 years of work and a combination of delay, obfuscation, mind-changing, foolish optimism, displays of technical ignorance and seriously neglectful supervision, London Underground's management finally agreed a contract with Thales for the re-signalling of the Sub Surface Lines (SSL). Thales is supplying a system broadly similar to the one they installed on the Jubilee and Northern lines with £761 million quoted as the contract price, albeit using radio transmission rather than inductive loop communication. Many railway professionals will be aware of the sad story that dragged on since the original contract for the SSL re-signalling was first signed in April 2003. The author was part of the process from the early stages.

In April 2003, a contract had been signed between the PPP private sector contractor Metronet and a consortium of Bombardier and Westinghouse for SSL re-signalling at a cost of £755 million. This was for 200 km of routes on the District, Hammersmith &

City, Circle and Metropolitan lines, using the same technology as installed later on the Victoria line and now delivering 36 trains per hour. In 2007, Metronet went into administration and, after deciding that the price was too high, LU decided to drop Westinghouse and pay them compensation of £95 million (Bombardier, 2008). This was followed by three years of searching for a suitable system until LU decided, in June 2011, to award a new contract to Bombardier Transportation for the same work but at a price of £354 million. This was less than half the original £755 million cost and had a 2018 target date. It was widely viewed by the industry as impossible and undeliverable. The author, in an article for the July 2011 edition of the magazine Modern Railways, wrote, "*Bombardier has a huge task ahead of it. Its signal engineers will not be familiar with the complex LU engineering philosophy and its rigid operating procedures and LU doesn't know the 'Ebilock' interlocking technology (remember the aborted Horsham installation?) nor the train control system*" (Connor, 2011, p.77). The Bombardier effort soon ended in tears. The author had received word in October 2013 that progress was slipping at a rate of six months every three months (Connor, 2014a) and that there was a move to get rid of Bombardier. This was publicly confirmed on 31 December 2013 when Transport for London (TfL) announced that the contract had been terminated with a £85 million pay-out to Bombardier (Connor, 2014b).

By now, there was only one supplier left who had the capability or the desire to bid – Thales. Siemens (as Westinghouse has become) had declined to bid in a competition with Bombardier and there were no other bidders. This was "a chalice from which no one would swiftly drink" the author was told (Anon. 2013). After 18 months of fractious negotiation, Thales and LU announced a contract on 3 August 2015 at a price of £761 million with a completion date of 2023 (RGI, 2015).

There was, externally at least, amazingly little fallout from what should have been a dismissal offence, for what the author considers to be gross negligence. Allowing for inflation, the original contract price was equivalent to £1.1 billion in 2017 so, at £761 million, it might appear that the new contract offers a good deal but it is not that simple. The project had already spent £180 million on Westinghouse and Bombardier in compensation and plus another £125 million of enabling works. This equates to £1.06 billion spent and, in addition, a nine-year delay to the completion of the improvements and loss of passenger benefits.

The author contends that neither London Underground's management nor its contractors had sufficient knowledge of the infrastructure and its operation to be able to appreciate the complication and complexity of the resignalling project. They expected that an off-the-shelf system could be adapted to handle movements across very constraining junctions and short interstation runs, with complicated service patterns.

London Underground’s network is a complex railway system whose successful operation depends on a variety of technologies, partly because it is an essential part of the capital’s infrastructure and needs to be cost effective and reliable and partly because the longevity of the equipment and infrastructure generally results in the systems outliving their management. The longevity often leads to corporate memory loss, aggravated in more recent times by the dispersal of railway management under privatisation and the splitting of infrastructure management from operational management. It is further aggravated by the changing social structure of work in the railway industry, where ‘a job for life’ is no longer the norm and job changes are an increasing occurrence in the life of an individual.

1.4 Problem Statement

Given the examples of the projects described above and other less than satisfactory projects, both from his own experience and his research into railway history, the author suggests that railway management is regularly failing to deliver engineering projects and solutions that are cost effective, that meet the stakeholders’ requirements and that are delivered on time. Not only that but managers also fail to learn lessons from previous successes and failures and sometimes carry their misconceptions or lack of understanding from one failed project into another. There is a real risk that such failures will be repeated.

There are far too many instances of railway projects that are poorly specified, underestimated from a cost or time point of view, badly executed or that do not deliver the expected outcomes. Few people in the industry today have the experience or the breadth of historical and current knowledge and understanding that is required to inform projects where systems are being changed or developed. In addition, corporate historical knowledge is often ignored, even when it is retained within the organisation, because staff do not know it exists, they cannot find it or because they cannot see the need to consult it.

The problem is that, since many railway organisations have become fractured and compartmentalised, historical data is fragmented and therefore difficult to locate. It is held in many places, it lacks continuity and, where it is available, it is often viewed out of context. As a result, it is rarely used and cannot underpin the project decision making processes, leading to failures.

The problem gives rise to several questions: can one link project failures to loss of knowledge? Can one track the flow of corporate knowledge through historical data? Does the loss of corporate engineering and operations history exist in other fields?

This leads to the argument that an accessible historical narrative on past engineering and operational evolution is needed to support a good, robust strategy for the future development of a railway. In order to achieve this, the study considers whether it is possible to create systematically an accessible narrative of the history of the operational and engineering evolution of an organisation that includes the reasons for the associated decisions and the resultant learning.

1.5 Aim and Objectives

Given the questions above, the aim of this thesis is to demonstrate that, by understanding the history and evolution of a large and diverse technological and operational system, it should be possible to produce a useful historical narrative to support decision making in the future development and progress of railway projects and to reduce the risk of failures as described above. This historical narrative could then be used to aid planning for new systems or installations, guide the introduction of future technologies or the employment of new operational strategies for the railway, provide improved domain knowledge and provide useful information for the staff tasked with project development.

This argument is developed through a detailed study of various aspects of the technical systems on LU's rolling stock between 1890 and 2015. The main aim is to understand how and why these systems evolved and then suggest how this historical knowledge might be used to improve future technological innovation on LU. The Underground's railways make a good case study because they represent a complex system, because the company has a high political and technical profile and because it has a history that is reasonably well maintained and it has infrastructure and equipment with a long life expectancy.

In order to achieve this, the following objectives were developed, significantly focussed on a case study that draws on the author’s personal experience and knowledge gained within London Underground and his observation of the evolution of this major technical and operational system over a period of 50 years:

1) To establish a view on the current knowledge of railway systems, corporate learning and organisational development;
2) To locate repositories of information that relate to the way railway systems were developed;
3) To review these sources and evaluate for relevance and context, identify trends in the ways in which systems were developed and the drivers of development and what the results were;

4) To determine whether corporate memory loss and path dependency experiences in the wider business and engineering worlds showed any similarity to those experienced in the railway industry.
5) To demonstrate that it is feasible to produce a useable historical narrative that is continuous, sequenced, integrated, contextualised and is accessible.
6) To show that the narrative can be used beneficially and profitably.

In parallel, the author has also noted the results of changes to management that might have had an influence on the development of the London Underground and the progress of its projects and how these might have affected the corporate memory. A search was conducted for sources relating to the theory of technological history and the foundations of the theory of path dependency and how these relate to the case study.

1.6 Overview of Work Done

This thesis is based on research carried out on the history of 125 years of electric rolling stock development on London Underground. The primary source of information was the constituent companies' records based at various locations around London. Some of these records included company board papers and minutes of meetings, engineering drawings, maintenance instructions, equipment records and rolling stock records. Secondary resources included books, photographs and published papers.

Examination of the sources was carried out over a long period, starting with review of a number of books on the development of rolling stock design on London Underground and on the development of London Underground as a system. This was followed by researching the company records available in public records offices and by examining the internal records through the author's employment on London Underground.

The data from the research was divided into subject streams so that the evolution of particular rolling stock systems could be compared over the period of review, in order to detect and clarify trends. Three of these streams were selected for their diversity, namely, electric traction control, car body design and bogie design, in order to obtain a robust sample for the research. Based on this data, a useable historical narrative was produced along with recommendation for its use in managing the future development of the organisation.

The author also discussed his research with many peers and colleagues, notably to identify how learning from history could be integrated into modern approaches to system operation, such as configuration management, rich requirements and rich traceability.

1.7 Overview of Methods Used

The research for this thesis was exploratory and qualitative in nature, comprising a literature review, a case study and participant observation of practice. The literature sources included:

- Books and reports from different sources;
- Company records and archive information;
- Academic journal papers;
- Opinion pieces and articles in the railway press;
- Monographs.

The case study is based on London Underground and the development of its rolling stock and comprises a document analysis of relevant company board meeting minute books and reports, internal documentation from London Underground and its predecessors, project reports, workshop instructions, engineering drawings and photographs. Some of the company records were accessed from British Transport Historical Records and these include London Underground constituent companies' minute books.

Participant observation was provided through 25 years of the author's direct employment on London Underground, employment with a manufacturer of LU rolling stock and six years as a consultant for LU projects.

During the course of the research, a triangulation exercise was conducted as more information became available and a number of new books were published, thus covering a range of approaches to describing the history and evolution of London Underground. These were brought into the research and were used as a comparator against the sources already used.

The data collected was analysed for patterns in the evolution of the rolling stock and for evidence of learning from experience. Changes in strategy were noted for each of the various railway companies that formed London Underground until 1933. Comparisons were made and trends noted. Various problems in rolling stock use were detected and further research was conducted to see if or how they were solved.

As could have been expected, the author noted some discrepancies in the recorded descriptions of events or systems and, therefore, he compared different sources to reduce the risk of errors or to validate dubious statements. Photographs were included in the research to aid identification of designs and technical solutions. In all cases the author used his experience to judge reasonableness of statements or records read.

A review of the literature was also carried out to determine what had already been researched in respect of the use of learning and experience in the railway industry. The author also included literature relating to corporate knowledge and how it was managed.

1.8 Overview of Findings and Conclusions

The thesis demonstrates that a useable historical narrative can be produced. The principal contribution to knowledge is that the author shows clear examples which demonstrate how the use of domain knowledge and the history of development has provided useful guidance for new projects.

This work is centred on a case study that describes the evolution of some of the systems used on the London Underground network during the 125 years of its electric traction history. It shows that this history has shaped the system and is still shaping it today. One example in the case study is provided by the development of electric traction control on LU where the investigation showed that, after 20 years of relying on a sole supplier, trials with alternative suppliers were undertaken. Unexpectedly, these demonstrated the superiority of the products of the original supplier and guided the procurement of new systems for the next 50 years. Another example concerns the evolution of the car body design and the associated features, such as the arrangements for seating and door positions and the operation of powered doors, where the experience of increasing traffic and the management of station dwell times showed the need for more doorways at the expense of seating. It also informed the approach to door safety systems.

A third example is from the development of bogie design. The original cast steel motor bogies, designed in the United States and supplied for the District and tube railways in London in 1905-1907, survived for over 20 years on the tube railways but were quickly shown to be totally unsuitable for service on the District Railway. The majority of those on the District had to be replaced by a completely new design within five years of service. The conclusion is that the difference in performance was because the type of track construction in the tunnels of the tube lines was more rigid and robust than on the surface and subsurface routes of the District. This experience informed bogie purchase for the next 30 years.

The case studies show that, because of the longevity of the infrastructure and systems, there is a need for an understanding of past development and experience and, therefore, the writer proposes that railway organisations should include in their business model a knowledge-based process that is used to inform the engineering (and other) decisions that are made during project development. This will require active development of an accessible historical archive and of a corporate development process that requires project management to include reference to previous experience held in the corporate knowledge base. The discipline of systems engineering may well provide some of the tools to achieve this.

1.9 Critical Reflection on the Study

The author of this thesis recognises that a study of this type is bound by certain limitations, not the least being the reliability and details of the sources used. It is also necessary to allow for a degree of scepticism in considering historical data.

“History” it is said, “is written by the victors”. These days, the phrase is regarded as axiomatic and, even in a study of the type presented here, dealing largely with engineering and operations issues and associated details, it is difficult to say exactly what has happened in the past because all that is left for the researcher is the paperwork recording the original authors’ version of the events.

In this research, some of the company board minutes were noted to be at odds with what is recorded in the engineering data and there was at least one instance where the writer of the minutes appears to have transposed two digits in recording the number of vehicles involved in a modification programme. The author cross references research details as far as possible with available alternative sources, such as photographs and drawings.

Consideration was also given to the differences between primary and secondary sources and debated as to whether photographs should be considered a primary source. The conclusion was reached that a photograph is not modified by evaluation, although it might be by alteration, and can thus be considered a primary source.

In more recent times, some of the published accounts of previous projects show a very liberal interpretation of what the author had experienced as a participating employee and, therefore, he has attempted to find alternative sources on the historical details in order to improve the accuracy of the work. Some of the research has used confidential internal documents that cannot be published. Nevertheless, there is sometimes a degree of personal interpretation applied results, based on the author’s experience and his knowledge of the various sources used.

1.10 Structure of the Thesis

The structure of this research extends across a case study covering various aspects of the evolution of technical systems on the rolling stock of the London Underground over a period of 125 years, between 1890 and 2015. The work covers several examples of rolling stock developments, covered in individual chapters, where each chapter includes a summary of the development and the lessons learnt. At the end of each chapter, there is a summary of the development process and its potential.

Chapter 1 is this introduction;

Chapter 2 is the methodology where the approach and the uses of primary and secondary sources are described. There is also an assessment of the use of personal experience in the research as applied to this thesis.

Chapter 3 is a literature review. It is subdivided into 14 sections to discuss particular topics that flow into the case study and the recommendations. These range from the need for order and discipline on the railway because of the nature of the fixed guidance system, the low friction of the wheel rail interface and the need for military style governance in order to provide safety and reliability. The review also covered the move towards privatisation, the subsequent reorganisations, the reduction in management expertise and the resulting loss of corporate memory.

Chapter 4 introduces ’The Heritage of the Tube’ in describing the background to the present Underground system and includes details of tunnel construction and the two sizes of trains. It also describes the original electric traction schemes adopted on the three pioneer tube railways in London. The purpose of the chapter is to set the scene for the research and to explain the origins of electric traction in London.

Chapter 5 is called ‘Dreams & Wheelbarrows’ and is used to describe the inventions of American engineer F.J. Sprague relevant to the operation of electric traction systems in London and his desire to see the replacement of steam traction on the Circle line by electric traction. It shows how the development of multiple-unit control traction allowed the expansion of urban railway capacity. It also demonstrates the start of the corporate learning process as it affected rolling stock development.

Chapter 6 covers the introduction of large scale electric traction in London and its subsequent technical development up to the present day. It shows how the experience of urban railway operation and maintenance in London was applied to rolling stock traction equipment development and how learning was applied (or not) and what the results were.

Chapter 7 describes the evolution of tube car bodies. There have been some significant steps in the past that have shaped what is done today. The chapter shows how operational experience at stations drove the need for improved car body design and the arrangements for doors and seating. It also shows that the constraints of the tube tunnel dimensions have restricted the design options that have been the same since the early 1930s.

Chapter 8 describes developments in bogie design and the difficulties in getting a durable and reliable system to work on London Underground track. The different approaches are described and their performance is assessed. The resulting lessons are noted.

Chapter 9 contains discussions on the literature reviewed and the various case studies. There is a discussion on some of the lessons learned from the case studies and the results of the research. There is a proposal to use of some of the formal tools offered by the discipline of systems engineering to create a methodology for implementing learning from history.

Chapter 10 contains the conclusions resulting from the research and recommendations for railway projects and future research.

2 Methodology

2.1 Introduction

In this chapter, the research approach and the specific methods used are described. The research was exploratory in nature, using an inductive approach whereby information that had been collected was analysed critically in order to develop a theory. The researcher applied a mixture of methods using both quantitative (i.e., measurement of data) and qualitative (in depth analysis) information from different sources supplemented by the knowledge that the author had gathered during his employment. He used this experience to selection, assess and interpret information.

The interpretative analysis revolved around the identification of patterns and themes from within both the quantitative and qualitative information and allowed an element of triangulation between the different sources. The intention was to create a usable history; to provide an analysis of past events with the intention of allowing it to influence current and future policy.

The analysis demonstrated that a useable historical narrative can be produced for the London Underground context and showed with clear examples how the use of domain knowledge and awareness of the history of particular development provided useful guidance for new projects. The study also shows that similar approaches can be adopted for different contexts, whether relating to railways or other long-lived asset rich environments.

2.2 Approach

To develop a detailed understanding of the subject, the data search included publicly available literature and case study company documentation, engineering drawings, technical papers and rolling stock records and this was related to the author’s own experience of 25 years’ service with the organisation, much of it working with rolling stock, as an operator or engineer. The combination of these sources has been used to analyse how the management of the technical and operational requirements evolved and what factors drove the solutions that resulted.

The information used fell into the broad categories of primary and secondary sources divided into quantitative and qualitative types as shown in Table 1.

Type / Nature	Primary	Secondary
Quantitative	Public Records Technical Specifications Purchase & Delivery Dates Engineering drawings Technical journals	Technical journals Trade magazines
Qualitative	Company board minutes Photographs Experience	Historical books Editorials; Opinion Pieces

Table 1: Categories of Sources.

The data and information relating to these sources were collected from a range of repositories, as detailed in Table 2.

Type/Archive	Population Size	Sample Size
British Transport Historical Records	674 indexed volumes	46 company record volumes and minute books
Acton Works Correspondence Office	Approximately 600 box files	All reviewed for relevant information.
Acton Works Drawing Office	4000+ Drawings Shop Instructions	300+ selected as relevant. 3000 files noted.
London Transport Museum (LTM) Archives	Approximately 1400 files on LU subjects	Reviewed for specific relevant records
Books in LTM Library	6000	60 selected
Photographs	700+	700+
Journals	Total unknown	Approximately 50 series of volumes.

Table 2: Selection of sources from archives and data stores.

During the early period of the research, the author acquainted himself with the various sources available, beginning with discussions with interested colleagues, followed by visits to locations where information was said to be available. This led to further discoveries of document storage locations and libraries. With each area of research, more experience was gained in determining the veracity of the data available and the whereabouts of further sources.

2.3 Primary Quantitative Sources

2.3.1 Public Records

A major source of information for this research was the corporate records of the railway companies that were combined to create the London Underground. They are catalogued under the former British Transport Historical Records (BTHR), now part of the London Metropolitan Archives.

2.3.2 Internal Records

Two main sources of London Underground corporate internal information were available to the writer during the years when this research was being carried out. One was the main rolling stock engineering drawing collection at Acton Works, subsequently removed into the London Transport Museum (LTM) collection; and the other was the Acton Works Correspondence Office records microfilming project that the author had responsibility for during 1981-1982. During this time, the author had to select files from the Correspondence Office that were to be microfilmed for long term retention. This provided him with access to a data source that went back as far as the early 1900s. It included technical specifications, equipment purchase and delivery dates and information on reliability and instructions for modifications to be carried out.

2.4 Secondary Quantitative Sources

2.4.1 Technical Journals

A range of technical journals were reviewed to assemble relevant papers covering the technical development of London Underground rolling stock. Some of these provided detailed accounts of the original construction and supply of routes and systems. Later papers provided accounts of how trains were designed and developed and the results of their performance in service. Some of the papers reviewed contained information that could be classified as a primary source and some as secondary. Information from these papers has been used throughout this research and is referenced accordingly. The writer also reviewed a number of papers on corporate memory, path dependency and the theory of technology during the project. These allowed him to form a clearer view of the problem. These are discussed in Chapter 3, ‘Literature Review’.

2.4.2 Trade Magazines

Throughout the period under research, articles in trade magazines described the introduction of new trains and systems, both with and without sponsorship by suppliers. These provided useful contextual information as well as drawings and photographs. Some contained detailed technical descriptions of, for example, traction control or braking systems and car body designs.

2.5 Primary Qualitative Sources

2.5.1 Board Minutes

Michael Robbins (1967) wrote, “the history of a railway cannot be written from minute books alone”. In the author’s experience, he was right but, nevertheless, the minutes of the board meetings of the companies that came together to form the London Underground system are a useful source of data relating to the major purchases of new equipment and rolling stock and, to a lesser degree, the alterations carried out on them, in the early days at least. However, there were wide variations in the quality and detail of minutes. Also, the dates of the recorded minutes may not always correspond with the dates the work or order was actually carried out and it is essential to check deliveries and actual dates of action wherever possible. In some cases, an order is noted as agreed at board level but not necessarily carried out immediately or even at all.

2.5.2 Photographs

A careful selection and review of photographs has provided the author with a number of useful checks and confirmations of other sources, such as company records and published magazine or journal articles. In particular, the LT Museum photographic collection is well known to the author and, as a result of his research, he has been able to correct some of the erroneous captions seen on the collection’s website.

The use of photographs has been coupled with inspections of drawings, contemporary journals, maps and other published works in order to obtain an accurate description of the subjects and to confirm what work was done or not done.

2.5.3 Experience

In this work, the author has included some of his own experiences and his participation where appropriate and relevant to the case study. The author considers that the addition of his personal experience can provide a usefully different or confirming perspective for a process recorded or for the results of an event. It can also provide background to aid understanding or to offer a rationale for the recorded event or decision. In dealing with history, it may also provide a useful validation of how work was actually done rather than how it was supposed to have been done. The author recognises that such comments are of a subjective nature, inevitably, and he always advertises such additions as his own views.

The author had completed an MSc programme in Railway Systems Engineering and this experience has also shaped his thinking and approach to problems. It has allowed him to be more critical in his analysis of situations and issues.

2.6 Secondary Qualitative Sources

2.6.1 Books

There is a large body of historical literature that refers to the London Underground system. It is of variable quality. Some is excellent and well researched, such as ‘Rails Through the Clay’ (Jackson & Croome, 1962), a history of the tube railways that originally stimulated the author’s interest in the history and development of the London Underground system, ‘London’s Metropolitan Railway’ (Jackson, 1986), ‘The Waterloo & City Railway’ (Gillam, 2001) and various shorter books by M.A.C Horne on each line, published in a series by Capital Transport Publishing. These authors based their contributions on sound research and provide sources that are useful for triangulation.

An excellent resource is a book by Philip Dawson, ‘Electric Traction on Railways’, published by the journal, ‘The Electrician’, in 1909. This extensive volume contains detailed descriptions of the contemporary electric traction systems available around the world, including those of the London Underground railways. It includes power supplies, traction control, rolling stock and bogies. It has proved a useful source of data.

Other literature has been consulted and referenced as appropriate, but some of it is less well researched and has been used as a sense check against some of the more obscure suppositions about how systems developed.

2.6.2 Opinion Pieces

The research has discovered a range of opinion pieces and editorials that offer views about the development and success of LU rolling stock performance and engineering over the years. These have been considered and noted as appropriate.

2.7 Participant Observation through Personal Experience

The author considers that researchers will, in the course of their work, be influenced by their own experience, particularly if the research is related to their professional past and current activity. Whilst they must try to maintain rigour in their research, some influences will remain and this will, to a greater or lesser extent, affect the direction of the research and how the researcher views his sources and conclusions. This may be considered a hindrance or an aid but, it is believed, used carefully and referenced appropriately, personal experience can be an aid to research.

In respect of this thesis, the author has used his personal experience alongside the conclusions from the research for his case studies and he feels that this is acceptable, provided the reporting of the experience is clearly positioned as experience without a literary or statistical reference to substantiate it. Some useful remarks on this subject are in a paper “Research Methods – a Case Example of Participant Observation” (Iacono et al, 2009).

The author has over 55 years’ experience of working in the railway industry around the world, with over half that time working for London Underground in various roles, ranging from platform attendant to senior management positions, responsible for both financial and technical implementation of large projects. The early years of this career comprised front line experience in railway operations, including three years as a train guard and another 10 years as a driver, dealing with the public (sometimes in hostile situations), coping with accidents and failures and sometimes acting in an ad hoc supervisory role in emergency situations.

In later years, after periods of working in train maintenance workshops and training, (including graduates), the author was sent on international residential assignments as a consultant and, subsequently, worked on various major railway projects around the world. The author is currently working as an international railway systems consultant.

Unavoidably, as a result of his experience, the author has retained memories and developed certain views that he has used in this thesis but, as noted above, such experiences have been indicated as such without necessarily having a documented reference.

2.8 Analysis

The analysis of the data and information collected was carried out in stages, beginning with the creation of a timeline to trace the progress of rolling stock development and its deployment on the various lines of the London Underground. The timeline offered a view of the initial procurement and development of the rolling stock and systems and this provided a background against which the service performance and success or otherwise of the original designs could be measured. Once an understanding of the distribution of the fleets was established, a view was obtained as to the success or otherwise of the original purchasing policy and how stock performed on different lines.

The timeline demonstrated that the delivery and withdrawal of rolling stock and equipment and its replacement showed different trends on different routes and for different suppliers. These trends were noted and traced throughout the period under study. Information on the vehicle record cards was recorded and the resulting totals sorted to provide a comprehensive record of rolling stock owned. The company annual returns of rolling stock provided useful checks for acquisitions and official withdrawals. The analysis provided an overview of the procurement strategy and life cycles of various ranges of rolling stock.

Where records showed an unexpected trend, this was noted and a further examination of the records covering the prevailing circumstances was carried out and additional research using other sources was undertaken. This was particularly the case for any significant modifications involving early replacement of parts or systems or for intrusive structural modifications on vehicles. A check on a record of purchase in a company's board minutes was confirmed (or not) by reviewing engineering drawings, looking for further minute book entries and examining photographs of the relevant vehicles. Further confirmation was provided by vehicle record cards that showed major items of equipment fitted.

The next task was to integrate the relevant parts of the information found and to create a usable historical narrative. As the narrative evolved, certain trends and links became apparent. These were evaluated, commented on and recorded in the narrative.

The narrative involved a range of different events, systems and technologies and resulted in a body of text amounting to over 150,000 words. The subjects covered a total of seven broad themes relating to rolling stock use and development, of which three were selected for further analysis. The choice was driven by a requirement to cover a diverse range of examples for the analysis so as to provide a broad base for the research outcomes.

The analysis shows that a useable historical narrative can be produced for the London Underground case study. It provides examples that demonstrate how the use of domain knowledge and the history of development can provide useful guidance for new projects. However, it was not possible to verify or validate the results of the analysis by following from start to finish a project that had benefited from a formal process to capture and apply learning from history.

The analysis provided information for the preparation of findings and recommendations for further work and for applications to current railway business management.

2.9 Summary

In this chapter, the methodology adopted for the research and analysis has been described and the type of sources has been listed and categorised. The introduction has provided an outline of the chapters and notes how the research revolved around the identification of patterns and themes from within both the quantitative and qualitative information and how it provided an element of triangulation between the different sources.

The next section dealt with the approach adopted for the research and it showed the range, locations and quantities of the sources accessed during the research. Tables were provided to display the data in an accessible format.

The writer then examined the sources in detail, showing each category of primary and secondary sources and then the quantitative and qualitative sources. The sources covered official records, reports, books, journal papers, opinion papers, engineering drawings and photographs.

The next section of the chapter described the author's consideration of his participant observation through personal experience. It is noted that personal experience has been used to aid interpretation of the information generated from the document based research and to provide possible reasons why events unfolded the way that they did. In addition, the author mentions that, used carefully and referenced appropriately, personal experience can be an aid to research.

The final section of the chapter describes the approach adopted for the analysis of the data gathered from the research. It describes how the construction of a timeline was used initially as a framework for the analysis and how it helped to set out the fleet distribution and usage. This was followed by an analysis of the longevity of the different types of fleets used and of the reliability of their equipment. Triangulation was used to validate, as far as possible, the events recorded in the various sources. The analysis was developed around a historical narrative covering three case studies and was then used to develop findings and recommendations.

3 Literature Review

3.1 Introduction

In this chapter, the writer reviews literature on the historical development and retention of knowledge within the railway system, how this knowledge was and is used and what part it played and plays in the development of the railway as a system. He then examines the changes that have occurred as a result of the privatisation of the British railway industry and the accompanying changes in the knowledge base, the continuity of service, the development of projects and the day to day operation of the railway.

In addition, a search has been conducted for literature relating to the relationship between large-scale corporate changes and knowledge retention and has sought to understand the relationship between railway development and path dependency.

3.2 The Orderly Railway

From the earliest days of railway operation, it became evident that, if a railway was to work effectively as a business, it had to manage itself in an orderly manner, with trains operating in a regulated fashion, equipment kept in a reliable condition and operated by staff who knew what they were supposed to do. The principal reasons for these requirements were the guided form of the railway's motion, the stiffness of its interfaces and the relatively limited coefficient of adhesion between wheel and rail.

A conventional railway operates with inside-flanged wheels on a fixed guideway or track formed of two steel rails laid to a fixed gauge on a supporting base constructed from sleepers[2], ballast, sub-ballast and track bed or a continuous concrete slab. The wheels of railway vehicles must remain on the fixed rails and thus provide a predictable path for the train (PWI, 1993). Deviation from the path is not permitted, nor should it be possible. There is no driver-controlled steering mechanism as found on a road vehicle, the combination of wheel and rail profiles of the railway providing the guidance. Railways thus require special infrastructure components to allow the overtaking of trains or the divergence of routes, that is, S&C (switches and crossings) (PWI, 1993).

Whilst providing a seemingly simple and predictable method of operation, trains have a disadvantage over road vehicles in that the guideway is not flexible. If there is an obstacle on the track in front of a train, the train has nowhere else to go, since it cannot deviate from its line of route. It will either stop before reaching the obstruction

[2] British terminology is used throughout, e.g., sleepers would be referred to as ties in US parlance.

or it will run into it. Trains cannot swerve out of the way. This restriction also introduces another reason behind the need for the orderly railway, the nature of the wheel-rail interface.

3.3 The Wheel-Rail Interface

The introduction of the steel wheel on the steel rail in the early 19th century provided a degree of efficiency of movement unheard of on a conventional road. The high stiffness of the wheel-rail interface and the reduced friction allowed a locomotive weighing 4 tons to move a load of 30 tons at 6 mph for 10 miles, something impossible using horses and carts on a road (Pearce 1996), even though the level of adhesion was considerably lower on the railway. With the continuing development of locomotive design and power, speeds and loads increased and trains very soon became increasingly efficient but, also, increasingly dangerous, since the low level of adhesion made stopping difficult.

For the new railways, the difficulty in stopping trains developed into a serious problem. Originally, locomotives did not have brakes, relying on limiting the operational speeds and compressing steam and air in the cylinders when necessary to slow down. The trains that they hauled had crude, hand-operated brakes on some but not all vehicles, requiring the use of 'brakemen' located along the train. Continuous vacuum and air brakes, controlled by the driver, did not appear until the 1870s. In the meantime, strict rules for railway safety, enforced by various Regulation of Railways Acts brought into law between 1840 and 1893, had to be developed to reduce the number of what became known as movement accidents. In devising these rules, the railway companies used a military approach.

3.4 The Military Railway

The inadequacies of braking and the lack of an obstacle avoiding capability in the fixed guidance system required a disciplined approach to the management of trains if they were to operate effectively and safely. Locomotives and equipment were expensive and had to be designed effectively, maintained properly and operated safely if the railway was to remain in business. Not all railways achieved the necessary performance, and breakdowns and accidents were common in the early years of operation. The better railways soon adopted a more disciplined approach and they realised also that the modern military organisations of the time offered an example that they could adopt (Ellis, 1954; Schmid, 2001).

A successful military approach was simple: Provide trained men, reliable equipment, a schedule and rules. Keep the men and equipment in good order and enforce the schedule and the rules (Fiennes, 1967). Deviation was not permitted without severe penalties. In wars, it had been proven over centuries that this strict approach was essential if success was to be achieved under combat conditions (Parker, 2005). Experience had also shown that the officers responsible for the troops and equipment had to understand their business and they had to be adaptable in times of crisis.

So it became for the railway. With expensive equipment, a large workforce, long, thin lines of communication, tight schedules and the need for strict rules, the parallels with the military were all in place, and military men had the ideal background for railway management. McKenna, in the book ‘Victorian Railway Workers’, wrote, “The railway discipline stemmed partly from the needs of the work itself - obedience, literacy, and punctuality - and partly from the expectations of railway officials, many of whom were from the army and used to controlling large numbers of uniformed and obedient men” (McKenna, 1976, p. 27).

In time, techniques in operations and engineering developed into sophisticated systems, led by technocrats and military-style officers and staffed by expert artisans and operators. The author was part of this system for 25 years and his career developed within it. The learning generated by staff experience was considered valuable by the railway companies, particularly as they did not pay for it directly. Initially, there was little formal training but this gradually improved into wide-ranging instruction both on and off the job. The author was involved with providing lessons and the administration of training for five years of his career and he grew to realise that companies needed to retain staff if the training was to pay for itself. Companies realised that the skills and experience developed by staff with their length of service were valuable assets that were expensive to replace. Staff were encouraged to remain, not only by pay increments but by offering good prospects for promotion.

A reliable and able member of staff could get promotion ’through the ranks’ and, eventually reach “officer” level (McKenna, 1980). This applied on the Underground, which took on many ex main line staff at all levels, including senior management, in the early 1900s and these men brought the main line railway traditions and values with them. The ethos of staff retention within railway service led to the concept of a job for life (McKenna, 1976, p. 31). The combination of the corporate policy towards staff experience and retention and the desire of staff for job security benefitted both parties and thus could positively influence the system’s performance.

3.5 Officers and Men

Railways quickly adopted military style rules for operation and military style discipline for the conduct of staff. From the 1840s, uniforms were provided for almost all operating employees, with the exception of the most senior officials, who were expected to dress appropriately: stationmasters at larger stations, for example, often sported morning dress when on duty.

Military terminology was widespread. McKenna (1980, p.27) records that Victorian workers who joined the railway, ‘joined the service’. When they arrived for work, they ‘reported for duty’ and when they left, they were only allowed to go if they had been ‘relieved’, like a sentry on guard duty. These terms were still the norm in the early 1960s, when the author joined the service, and many are still in use at the time of writing.

Railway artisans and operators were classified as ‘men’ and senior managers as ‘officers’. This lasted into the 1980s, when the author recalls being informed that he was, having being promoted to the grade of Executive Assistant, now permitted to use the ‘Officers’ Dining Room’ at the workshops where he was employed. Using the facility for the first time was a revealing experience, with its table service and (subsidised) restaurant quality food. He quickly got used to it.

3.6 The Corporate Knowledgebase

As they grew, the new Victorian railway companies quickly developed a wide and diverse knowledgebase. They loved paperwork and documented every process and business transaction; tickets, for example, on collection at the ticket barriers, would be sent to the Railway Clearing House for accounting purposes (McDermott, 1904, p. 108 et seq,). Rule Books were developed and staff were required to learn them. Everything to do with the operation was written down (McKenna, 1976). Notices were issued to staff about changes to the timetable, line, stations, signalling and rules. Time was allocated for train crews to read the noticeboard at each depot and a ‘traffic notice’, or similar document, was a common weekly publication. In effect, this became a part of what might be called the corporate knowledgebase. Much of this paperwork has survived and has proved a valuable source for this research.

The collective knowledgebase included both local and centralised tacit knowledge. The railway corporate knowledgebase extended upwards through the management structure. Gourvish (1973, p. 77) wrote that, “As the industry developed, so too did its capacity to produce its own management material, and the companies were soon able to show a distinct preference for men with practical experience of railways.”

Until the early 1990s, a large proportion of middle and senior managers were promoted from the ranks (as was the author). As had been the case for earlier generations, their years of practical experience and their understanding of what to look for during problem solving or investigations became a valuable corporate tool. When problems arose, the right questions would be asked and, when new ideas were proposed, these home-grown managers had a better feel for what would work and, more importantly, what would not. This was within the author's own experience as a senior manager with LU who was required to attend executive committee meetings as a deputy director.

The same experience was used in planning and design across the organisation. Chief Officers would consult with their staff and with each other when preparing submissions to their board of directors for authority for improvements, changes to rules or new equipment requiring expenditure. If the advice from their staff was controversial or unusual, most officers had the experience and knowledge to refer back decisions or recommendations with suitable questions. Those who did not would be pushed into such questions by their colleagues. There was a demonstrable culture of corporate responsibility involving all departments and evidence of this can be found in records kept (e.g. LU, 1988; Morris, 2012)).

Although most of this chapter has referenced main line railways in Britain, the same story was seen on London Underground, which was, in the early days at least, partly staffed by people from main line railways around London (Yorke, 1912). The traditional railway hierarchy was very familiar to the author in his career on the Underground up to 1992.

3.7 Organisational Change

Beginning in the late 1970s, there was a gradual but important change in the way the railways in Britain were managed. Commercial behaviour, having been removed almost completely by the late 1940s as a result of the two great wars, when the management of the railways had been taken over by the government, and then nationalisation, began to be re-established as part of a Government-backed policy. With the privatisation of public utilities like telephones, gas and electricity, already in process, railways were being considered as possible candidates too. Tyrrall and Parker (2005) describe the transition to privatisation as occurring in two stages:

The first stage of commercialisation was the development of the 'Business railway', where the 'Public interest' was retained within policy but with increased pressure on the management to get 'business revenues'. There was "*more commercial orientation with emphasis on revenue surpluses and reduced government subsidies*" (Tyrrall & Parker, 2005, p. 514). To promote this, in 1982 British Rail's operations were reorganised from regions (basically the old post-grouping railway companies) into 'Sectors', like Intercity, Network SouthEast, Railfreight and Regional Railways, where business-type directors were appointed and then judged on their financial performance (Gourvish, 2002, p. 103-107).

'Sectorisation', as it became known internally, gradually led to a management shift from monitoring operating performance and keeping the assets in working order to a more financially orientated approach, where assets were sweated; track maintenance was deferred to reduce expenditure and rolling stock was allocated on the basis of where it would produce the highest income, regardless of its suitability. At the same time, money was, according to Tyrrall & Parker (2005), diverted to providing new and distinctive liveries and logos, in the pursuit of business orientation[3].

The second stage of the conversion to commercialisation recognised by Tyrall and Parker (2005) was privatisation, when the railways were supposed to become a ‘profitable business’. Privatisation was written into law by the Railways Act of 1993 (Bartle, 2005) and, in 1994, work started on the final break-up of the British railway system into Railtrack, 13 separate infrastructure maintenance companies, 3 rolling stock leasing companies, 25 train operating companies and numerous other smaller companies spun off from BR Research and similar internal non-core organisations (Harris & Godward, 1997, pp. 82-85).

With this conversion to a ‘profitable business’, Tyrrall & Parker (2005) noted that the railways moved from integration under their intermediate state as a ‘social railway’, through a state of ‘differentiation’ under sectorisation to ‘fragmentation’ under privatisation. The fragmentation was to have a profound effect on both the financial management of the railways and their knowledgebase.

3.8 Fragmentation

The fragmentation of the railway system following privatisation was quoted by Bartle (2005) as one of the reasons for the loss of the railway knowledgebase. He writes that, amongst other things, “*Extensive fragmentation has also led to a severe loss of institutional and organisational memory unsatisfactorily replaced by a complex maze of contracts many of which are incompletely specified and very difficult to enforce*” (Bartle, 2005, p. 40).

This issue was also raised by Mercer Management Consulting in a review conducted on behalf of the Government (Mercer, 2002) when they deduced that one of the principal problems with the rail industry at that time was that they failed to carry out correctly the maintenance and renewal of the network, largely as result of a loss of knowledge and expertise.

[3] The author’s own observations at the time were that signal gantries, cable runs, lineside fencing, and railway buildings were no longer repainted at regular intervals and eventually showed signs of rust and deterioration while weeds were to be seen growing on running lines, even within station limits, something previously unheard of. Regrettably, little has changed in many areas.

3.9 New Management

It could be argued that fragmentation in itself would not necessarily cause a loss of or even reduction in the corporate knowledgebase. After all, dividing an organisation into smaller parts might only move staff around or change their reporting lines. The knowledgebase could still be retained, even if the communication lines were more difficult.

However, with privatisation came new senior management. One of the features of company takeovers, for that is really what privatisation was, is that the old management is removed and new management brought in. Boyne (2004), using a selection of private sector companies as a model, describes the takeover process for a failing company as involving a combination of ‘the three Rs’, retrenchment, repositioning and reorganisation. Since the whole idea of railway privatisation had been based on the premise that railways were inefficient and needed ‘turning round’, it was inevitable that Boyne’s model, or something like it, would be applied.

In broad terms, Boyne says that retrenchment involves a reduction in staffing levels. This was quickly applied in the railway industry. In the five years from 1996 to 2001, the staffing levels in train operating companies dropped by 21% (Glaister, 2004) during an era when traffic levels were rising on all routes. Some operating companies cut back staffing to the point where they had to cancel trains (The Independent, 1997). South West Trains, offering drivers redundancy packages to encourage them to retire early, lost so many that they were unable to run a full service and had to re-recruit some.

Another feature of the corporate takeover described by Boyne (2004) is ‘repositioning’. This was not so applicable in the railway industry, since most of the companies had a local monopoly and did not need to reposition themselves other than establishing branding to show that the routes were under new management. However, repositioning might also be said to include a new and improved marketing approach, and this was widely seen after privatisation.

The third of Boyne’s takeover tools is reorganisation. He says, “*the form of reorganization that is cited most frequently in the literature on private sector turnaround is the replacement of the chief executive or the entire senior management team*.” (Boyne, 2004, p.99). In the privatisation of the railways, the latter option was the most commonly adopted. The rationale for this is explained by Glaister (2004, p. 2) when describing the ethos of privately managed companies, “*Conventional disciplines are supposed to apply whereby failure to do well for the shareholders would normally be punished through the competitive market for corporate control, the threat of takeover and replacement of the management*.” In the author’s view, since the railway's failure to do well was already assumed in the political decision to privatise, management re-replacement was inevitable.

In the railway's post-privatisation reorganisations, managers, many with long service, high salaries, and good pension conditions, the author included, were offered substantial incentives to take what was euphemistically called 'voluntary severance'. In effect, managers were told they did not have a job under the new order and were advised to leave without making a fuss. The (normally cash) incentives were carefully positioned to ensure compliance without recourse to law. Indeed, they were so attractive that, like the hourly paid staff, too many left and companies struggled to manage their operations. Many 'severed' managers were re-employed as consultants to assist. The author has made a living from it for 18 years.

3.10 Corporate Memory Loss

Railway managers taking 'voluntary severance' not only took large payments with them, they also took their expertise. The unrestrained culling of senior railway management that followed privatisation resulted in a corporate memory loss of considerable proportions (Brendan, 2002). Only the three rolling stock leasing companies (known as RoSCos) survived unscathed, largely because two of the three were set up as a result of management buyouts and all three retained most of their railway technology experts. The expertise stayed where it was needed and money was made. All the RoSCos were sold on to banks and investment companies within three years (McCartney and Stittle, 2012). The media-generated public outcry over how much money was made by some of the buy-out managers was such that a government enquiry was initiated (Competition Commission, 2009).

The general lack of technical expertise in the rest of the railway industry after privatisation was to leave many of the operating and maintenance organisations floundering (Cole & Cooper, 2002). The best known example is Railtrack, the original infrastructure management company set up by the Government for privatisation. Railtrack saw itself as simply a management company (Glaister 2004), subcontracting maintenance and renewals to external companies like Amey, Jarvis and Balfour Beatty, most of whom had purchased the maintenance organisations that had been created out of parts of the former BR organisation. Few of these companies had any railway management expertise left and some of them suffered as a result – the collapse of Jarvis refers (The Guardian, 2010).

The process of corporate memory loss is characterised by Annie Brooking in her book, 'Intellectual Capital', where she suggests that every time an employee leaves, a substantial amount of corporate memory is lost (Brooking ,1996, p.9). For the British railway industry, the ultimate example of the consequences of the loss of corporate memory was the Hatfield accident. As Glaister (2004, p.35) noted, following the accident, "*Railtrack all but closed the system: they imposed very wide and restrictive train speed limits and caused many train cancellations. Experienced railwaymen have said that they would not have reacted in this way and [Railtrack's] senior management received advice against the need to do it.*" There followed several years of poor timekeeping, falling passenger numbers and hugely increased expenditure on 'catch-up' track maintenance.

The Hatfield accident and the consequent destruction of effective railway services across the country was to lead to the collapse of Railtrack itself and the setting up of Network Rail in its place. Network Rail was formed partly on the understanding that there was a need for railway experience at a high level in its organisation and it was therefore set up with 8 of the 12 members on its board having railway experience (NR, 2004).

3.11 Understanding the Technology

The acknowledged loss of operational and technical understanding in the railway industry may not, in the author's view, be entirely due to the fragmentation of the industry and the loss of experienced staff. There have been other changes too. In parallel with the changes in organisation have come changes in technology – solid state power systems, plug-in hardware, optical cable transmission, GSM technology, software based control, satellite based mapping, social media and tablet technology are some of these. All have been developed in the last 25 or so years. These developments need new expertise and, in many cases, more, in depth technological understanding.

New technology is complex. Power electronics have replaced electro-mechanical systems, software has replaced levers and bell codes and microprocessors have replaced locking frames and relays. The complexity of the new technology means that it is no longer possible for the artisan to understand and troubleshoot a whole system. He (or she) has to be a specialist in say, communications systems, train control software or computer operation. He can no longer be the 'signal lineman', who could deal with most mechanical and electric signalling problems equally competently. Now, specialists are needed for each system. In itself, this will fragment the knowledgebase and this fragmentation, combined with the parallel fragmentation of the organisation into separate companies, reduces the integration, the co-operation and cohesion needed to make the railway system work effectively.

What is missing, in the author's view, is systems expertise. This requires an overall understanding that includes both the operational and engineering systems used on the railway and the interfaces between the systems. It also requires an understanding of the background and development of the systems and the reasons why they developed in the form seen on today's railway. The long-term nature of the assets – 30-40 years being the generally recognised norm for electrical and mechanical systems – means that a historical perspective has to be included to gain a proper understanding of the railway system.

3.12 Developing the Historical Perspective

Divall (2009) offered an argument for the development of a historical perspective. He wrote, "*Other things being equal, it is better to have the best comprehension we can of what was going on in the past rather than none, as long as we are clear about the limitations of that knowledge and its sources*" (p. 2). Developing Divall's theme in this thesis, the author believes that, in order for an understanding of the railway and its systems to be complete, a comprehensive historical record of the railway system needs to be developed. This would go a long way to recovering from the corporate memory loss experienced in recent years. To make this corporate memory useful, it also needs to have a convenient data access system, available to all who need it. There is no reason, given the capabilities of modern technology, why this cannot be developed, given time and money, perhaps using modern data retrieval systems like cloud computing. The difficulty might be in persuading people to use it.

The author also believes, that there has to be a succession plan for railway companies that allows some senior people to be long service staff who have been brought through the organisation and who have, as a result, developed a broad understanding of the railway and its systems and who have a network of relationships with people in the industry. Railway companies need again to provide the right sort of incentives to encourage staff retention and development.

3.13 Path Dependency

Another area of the research was in the field of the theory of the history of technological development. This was an attempt to determine what had been done in this area that might aid the research analysis or which might suggest patterns in technical evolution that would drive future development.

In this connection, path dependence and how it might be seen in relation to the pattern of development of the London Underground train was considered. The author first noted a definition from the Financial Times lexicon (ft.com, 2014) as follows:

"Path dependence is the idea that decisions we are faced with depend on past knowledge trajectory and decisions made, and are thus limited by the current competence base.

"In other words, history matters for current decision-making situations and has a strong influence on strategic planning. Competences that have been built in the past define the option range for today's moves."

There is, in this definition, some relevance to the loss of corporate memory in the railway industry described above, largely because the cost of equipment and infrastructure for railways is so high that it tends to survive for a long time (usually a minimum of 40 years for electrical and mechanical equipment, 60 years for buildings and over 120 years for the civil engineering works) and therefore the systems have to be embedded in the management and culture of the organisation. The whole system is therefore path dependent. If the management has lost its understanding of the infrastructure and systems it has under its control, decisions about changes to them or on their replacement cannot be made rationally or effectively; examples in Section 2.2 above refer.

Path dependence is described largely in literature in relation to economic progress, its causes and the factors driving or restraining it. The well-known book by Joseph Schumpeter (1934), 'The Theory of Economics Development', first written in 1911 and published in English in 1934, suggests that innovation is essential to business development but that invention is not. This is further developed by various authors, notably Paul David (2001), who believes that path dependence restricts the ability of organisations to change when necessary (2001, p. 19) and Rycroft and Nash (1998) who suggest, conversely, that path dependence is a powerful influence on the innovation of complex technologies.

In their paper 'Correlations between Past and Present Transport and Urban Planning Policies', Pflieger et al (2009), examine path dependency in the context of urban transport planning to try to see why some cities were more successful in changing travel habits than others. From their work, it would appear that changes were restricted by path dependency. The author questions whether this is valid for the railway system. In the author's view, there is evidence in London Underground's rolling stock development of both arguments, as will be seen in the case studies described in this thesis.

3.14 Project Management and Systems Engineering

As a direct consequence of the catastrophic Clapham Junction accident of 12th December 1988 (Hidden, 1989), Britain's railway industry adopted the discipline of project management (PM) to improve the way in which resources were managed on railway renewal projects. A few years later, the poor performance in managing major projects and programmes at the start of the Railtrack era on Britain's mainline railways led to the introduction of systems engineering (SE) to the industry. The former discipline deals largely with the appropriate and economic use of resources, while the latter is aimed at creating outputs that satisfy the aspirations of the stakeholders at an acceptable cost and in a reasonable time frame. Essentially, it is about ‘building better systems better’. At each stage in the process, the use of historical data should be incorporated. In the following paragraphs, the author provides a brief overview of formal SE approaches, since he will propose to adopt some of the associated tools to support the generation and retention of corporate knowledge in Chapter 9.

SE includes a range of activities and tools that are designed to ensure that stakeholders’ objectives are captured correctly and that a system delivers the correct outputs throughout its life-cycle, from cradle to grave. Often, systems engineers employ a Vee process (Figure 1) to develop new systems or to define projects (Estefan, 2007).

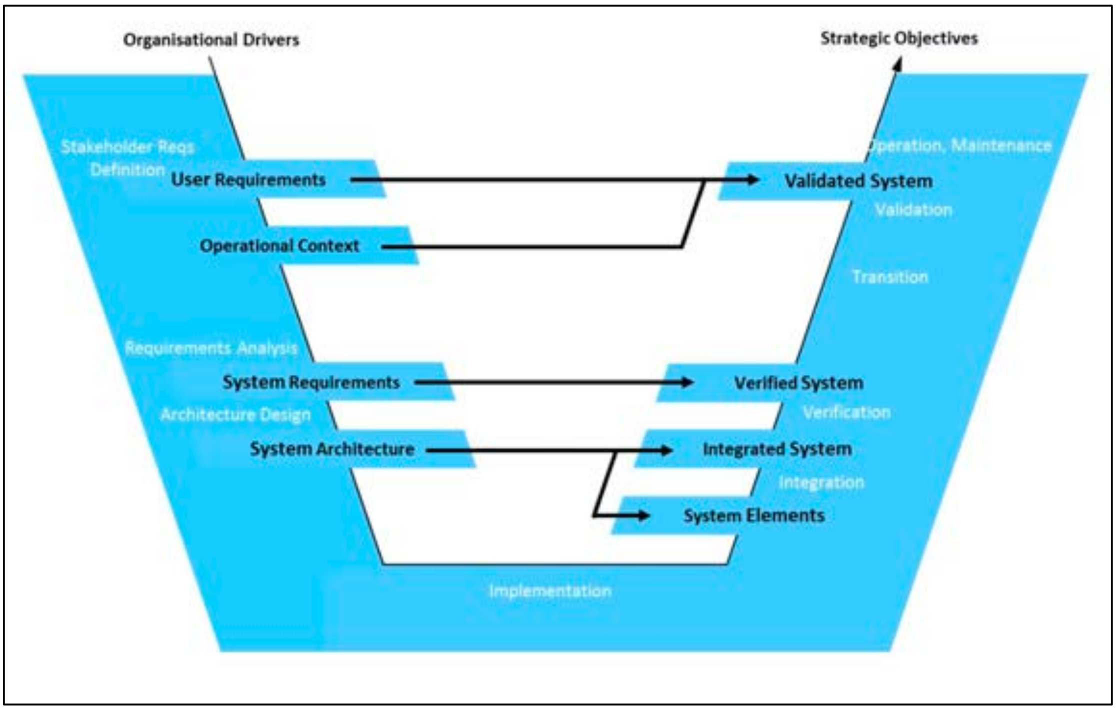


Figure 1: System Engineering V model. Source: Systems Engineering and Project Management Integration: V-model (Explanatory Note), APM/Incose, 6/11/2014.

3.14.1 User Requirements

In order to ensure that the strategic requirements of any project meet the expectations of the stakeholders it is essential at the start of the system engineering process that a set of user requirements is developed. A stakeholder may be defined as someone who has an effect on or will be affected by the project or its outputs (Ryan, 2014). There is often a wide array of stakeholders, ranging from the client, who may be the sponsor and financier for the project, to the operators and maintainers who will make the system work and keep it working. There will also be external stakeholders like landowners, local authorities, environmental and safety agencies and utility suppliers.

Once the stakeholders are identified and registered, the process of gathering the user requirements can begin. This often requires the use of an object orientated or relational database, where the user requirements are stored for use as part of the project design and validation process.

3.14.2 Requirements Capture

A requirement can be defined as the ability needed to provide the output of a project. The requirements are usually listed as project specifications. As noted by Githens (2000), "*The process of requirements specification is very important because when requirements are poorly captured or managed, scope creep can occur and imperil project success*". A rich requirement approach will provide the necessary detail. The author would propose that, at this stage, the historical perspective should be introduced into the process so that former requirements are noted and assessed and their results incorporated as necessary.

Once the requirements capture process is substantially complete, it will be possible to start on preparing the engineering specification. The process will include going through each process taken from the user requirements database and incorporating that into the design from which the specification will be derived. This process will have many variations depending upon the type of project and its scope. When the specification is complete, it will be necessary to validate the clauses in the specification with the requirements database.

3.14.3 Configuration Management

Once the project is underway, and the specification is being prepared it is essential to provide a system of configuration management. This is described as "the administrative activities concerned with the creation, maintenance, controlled change and quality control of the scope of work" APM (2018). This should include a rigorous system of change control. In the author's experience, the success of a project almost invariably depends upon the effectiveness of the change control process. It is important that this is begun at the start of the project and is meticulously enforced throughout.

3.15 Summary

In this review of literature on corporate memory in the railway industry, the author has examined the development of the engineering, staffing, structure and operation of railway systems and the adoption of a military-style management system. The consequent building up of the corporate memory was described, based on the need for system continuity and the desire of staff for secure employment. Moves into privatisation and the resulting exodus of experienced staff were noted and, with it, the loss of corporate memory and a reduction in technical competence. References were made to the loss of railway expertise since privatisation and, in particular, the over-reaction of Railtrack after the Hatfield accident in 2000, largely due its lack of experienced engineers.

In the context of the influence of history on development, in the literature on path dependency, there appears to be a two-fold influence on technological progress. One is what could be described as a ‘drag effect’, where innovation is restricted by a reluctance to change what is seen as the historical reliability of the current systems while the other is the need to ensure that path dependency is understood and utilised by the system’s management to ensure a viable approach to the development and introduction of new technology. The author’s case study on London Underground rolling stock development attempts to demonstrate these ideas.

The author also reviewed sources relating to system engineering processes to determine its possible use to incorporate reference to historical data in the development of specifications and projects.

3.16 Conclusions

The author’s conclusions, from the literature he has reviewed, is that it is widely recognised that the former railway business structure, based on a military style, vertically integrated organisation and an ethos of staff development and retention, has been replaced by a new structure that has resulted in a loss of corporate memory and a reduction in the capability and effectiveness of railway system management. The records of the failed projects described above show that there are serious deficiencies in the integration and knowledgebase of the railway industry both on the main line railways and the London Underground. This recent history shows that the lack of understanding of the basic engineering, economic and operational background of the railway system has resulted in some serious project failures and has affected the future prospects for political and financial backing for railway development. The author believes that an understanding of the historical background and past technical development of the railway system are essential for a project to stand a reasonable chance of success.

4 The Heritage of the 'The Tube'

4.1 Introduction

This chapter opens with a broad description of the London Underground railway system (known as "The Tube") to provide a background for the technical cases in the thesis. Since an understanding of the development of electric traction on the system is fundamental to understanding the subsequent technical progress and path dependency, the author examines the early, developmental phase of electric traction in London. The author's objective in this chapter is to provide a background for the case studies in his thesis and to determine if or where the chosen solutions of the pioneer electrification schemes could have been handled differently and what the results were. This examination of the early electrification schemes shows that options were limited by the technology available, by the conflict between affordability and the system offered and by an already developing path of dependency on what had been done before.

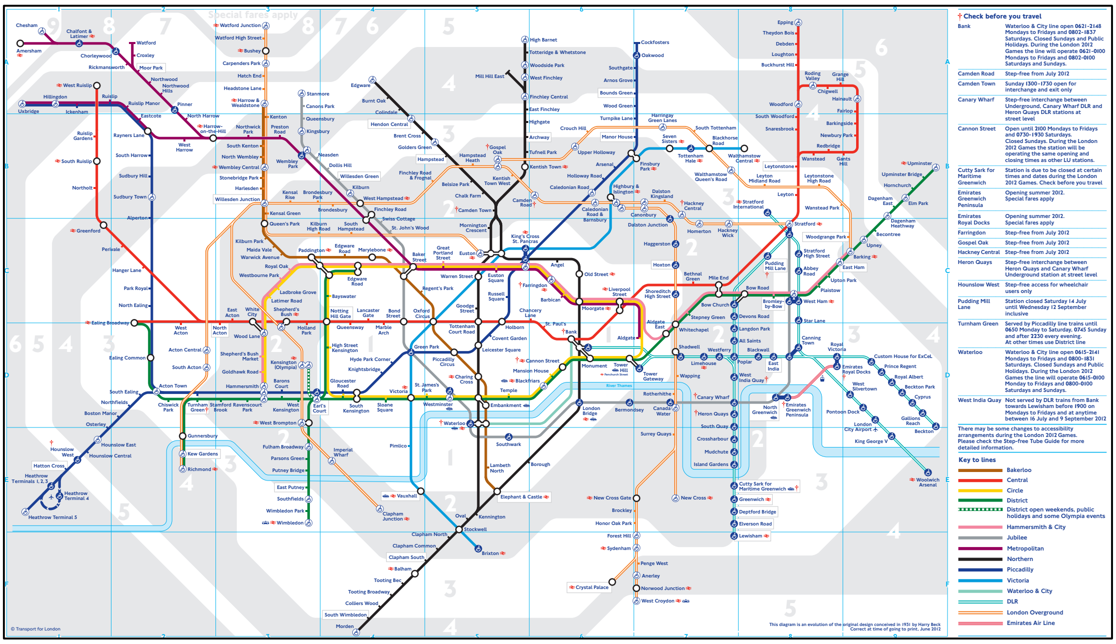


Figure 2: Official diagrammatic map of the London Underground system known as 'The Tube'. It includes other lines operated by TfL. Source: Download from www.tfl.gov.uk, 16th September 2012.

4.2 The London Underground

In order to understand the development of technical change on the London Underground, it is useful to review the system and the historical context in which it was developed. The London Underground, is the oldest of the world's many urban rapid transit systems, the first section opening on 10th January 1863. Its heritage was celebrated in style for its 150-year anniversary in 2013, including a visit by Her Majesty The Queen and members of the Royal Family and a re-enactment of steam operation between Edgware Road and Moorgate over part of the original route.

The Underground now has 11 lines and serves 270 stations, which provide services for up to twenty-four hours a day on some lines. The system is governed by TfL (Transport for London), a public body that is also responsible for the provision of some main line rail services (the ‘Overground’), London area bus service franchising and surface transport facilities in the greater London area, amongst other things.

The region known as Greater London has an area of 618 square miles and a population of over 8 million. Over a million people travel into central London each day for work and over 60% of these use the London Underground system. Between 2000 and 2015 there was a 70% increase in the demand for travel on the Underground so that, more than ever before, London relies upon the Underground system as part of the social and economic structure of the city. The number of passenger journeys is around 1.35 billion a year (TfL, 2017).

Figure 3: Tube and Surface stock on test at the Bombardier factory in Derby. The smaller train on the right is 2009 Tube Stock for the Victoria line, while the larger train is the S (sub-surface) Stock. The tube car floor is about 300 mm lower than that of the sub-surface stock car and the roof is 800 mm lower. A surviving tradition on the Underground is to identify Sub-surface Stock train types by letters and tube stock by the date of order, or close to it. Photo supplied by Ted Robinson.

This area within the Circle Line forms the commercial heart of the capital. The area known as ‘The City’, east of Holborn, is the financial district, while the ‘West End’ contains the principal shopping and entertainment areas. Until the beginning of the twentieth century there was virtually no penetration of these areas by railways but then the various deep level Underground ‘tube’ lines were opened and there is now a network of lines covering both the City and West End zones and connecting them with many of the suburbs. The routes going out to the suburbs rise to the surface outside the central area and, in fact, now some 55% of the London Underground route mileage is in the open.

The greater London area is geographically divided into two halves by the River Thames, which flows west to east across the city. In the north-south division that this causes, by far the greater proportion of the Underground system is located in the northern area (Figure 1). Of the 270 stations serving the system only 29 are located south of the Thames, due partly to old railway company economics and partly to the nature of the subsoil in the area, which rendered tube construction difficult and expensive. As a result, in contrast with the freight-rich railway companies north of the river, the southern companies depended very much on local passenger traffic for revenue and provided a dense network with frequent services, which had been electrified almost entirely by 1935. The Underground was not needed in this area and, indeed not wanted. The newly formed Southern Railway objected, in 1923, to the Bill for the proposed extension of the City & South London Railway from Clapham to Morden, which it regarded as an incursion into their territory and the LER’s Bill for the extension was dismissed by the House of Lords. Eventually, the SR’s General Manager, Sir Herbert Walker, reached a compromise with the Underground, which allowed the LER to build the line to Morden as long as there was no further attempt to extend the Underground into the Southern’s territory without prior agreement (Croome & Jackson, 1993, pp 150-151).

4.3 Two Sizes of Trains

One of the features of the London Underground is that it operates rolling stock of two different sizes (Figure 1). This is because, over the long period of its development, two tunnel cross sections were adopted, a result of the different methods of tunnel construction used. The original tunnelling method, used for the Circle Line and its extensions (now the Metropolitan and District Lines), is known as the ‘cut and cover’ method. With this method, a cutting is dug along the line of route just deep enough to take a main line-sized train and its track (Baker 1885a). When completed, the tunnel is roofed over and the surface restored, often with a road-way (Figure 4). Cut-and-cover construction is still adopted for shallow tunnels but the modern methods are less intrusive in that diaphragm walls are established first, the alignment is then excavated to a shallow depth to allow the installation of a concrete deck on which roadways can be reinstated, following which, excavation work takes place underneath.

Most of the resulting tunnels are just wide enough to take two tracks, except at stations where they are widened to take platforms and stairways. Because of their proximity to the surface they are often referred to in London as ‘the sub-surface lines’ (SSL).

Cut-and-cover construction is still adopted for shallow tunnels but the modern methods are less intrusive in that diaphragm walls are established first, the alignment is then excavated to a shallow depth to allow the installation of a concrete deck on which roadways can be reinstated, following which, excavation work takes place underneath.

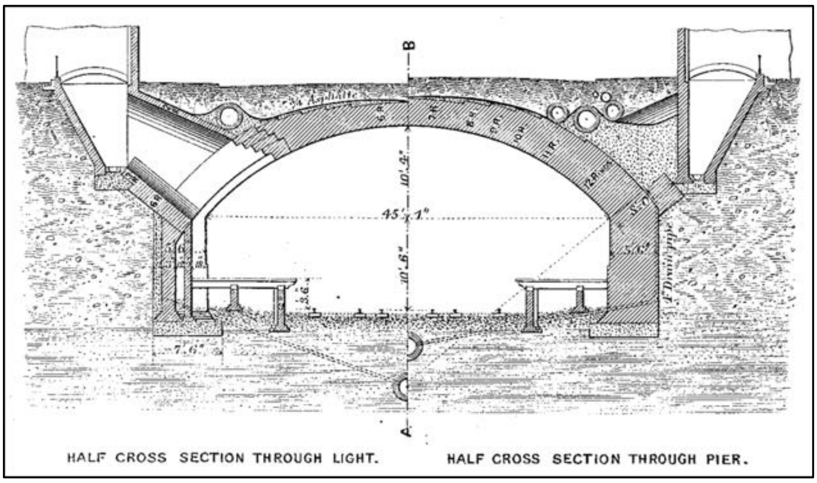


Figure 4: Cross section of the 1863-built Circle Line tunnel at Baker Street station (now Platforms 5 & 6) showing the original cut and cover construction that is still in place today. The arch and side walls are brick. The station tunnel was provided with angled shafts at intervals to admit natural light, seen on the left section. Note that the track shown is mixed 7 ft. and 4 ft. 8½ in gauge, to accommodate trains from the Great Western Railway as well as other operators. This section is wider at 45 ft. 1 in than the inter-station sections, where the internal width is 28 ft. 6 ins. Later tunnels were only 25 ft. wide as they did not need to accommodate the broad gauge track. (Baker, 1885b).

The second type of tunnel is the deep level 'tube' tunnel. This method of construction was adopted to overcome the huge surface disruption caused by the cut and cover method and it took advantage of the blue clay soil upon which London is built. Single track, circular tunnels of about 3.4 m diameter (11 ft. 8 ins) were bored at a level deep enough to minimise conflicts with water mains, sewers and other underground services. Tunnels bored since the late 1930s were built to a standard 12 ft. diameter on straight track and widened slightly for curves (Croome & Jackson, 1993, p. 249).

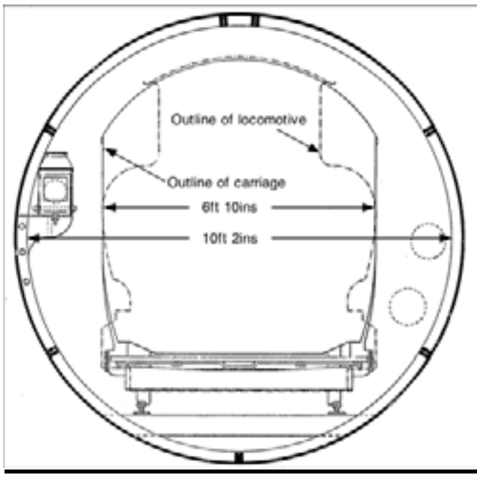


Figure 5: Cross section of C&SLR tube tunnel showing the profile of the locomotive and passenger car. The internal diameter of the original tunnels varied between 10 ft. 2 ins and 10 ft. 6 ins but it was increased to 11 ft. 6 ins on the Moorgate extension. A tube line required two separate tunnels, one for each direction of running. The older, sub-surface tunnels, were usually double track. Drawing: Adapted from McMahon (1899) by author.

Stations usually feature a large single-track tunnel for each platform. Station tunnels are generally 21-25 ft. in diameter. The greater depth of these lines (an average of 20 metres) meant that lifts or escalators had to be provided for street access. The technology of deep level tube construction was available quite early on in the development of railways but it had to await a practical means of propulsion that did not require the use of smoke and steam. At first, cable haulage was considered for London's first tube line, the City & South London Railway (C&SLR), but this was soon discarded in favour of electric traction (Lascelles, 1955, p. 7).

4.4 City & South London Railway

The C&SLR was London's first tube railway. It was opened in 1890 between King William Street in the City of London (near the Monument) and Stockwell. It used small, 4-wheeled, electric locomotives to haul a set of three passenger coaches. The original, single track, running tunnels were only 10 ft. 2 ins in diameter (Figure 5). Intermediate station tunnels were 20ft. in diameter and included both tracks and an island platform (Greathead, 1895).

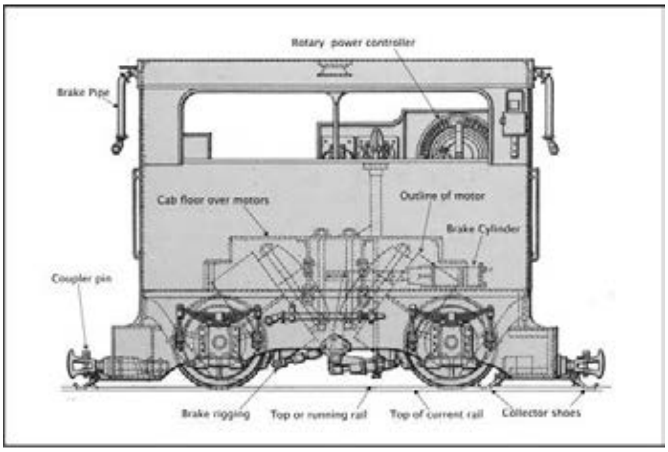


Figure 6: Scale drawing of early C&SLR locomotive showing the principal parts. One feature introduced at this time was the location of the brake pipe connection hose at roof level. The small bore tunnel restricted the height of the vehicle and there was no room for anything other than the link & pin coupler below floor level. The lowest floor level was only 30ins (762mm) above rail level. It had to be raised in two steps to clear the motors. Another unusual feature was the setting of the conductor rail height below that of the running rails. It meant that wooden ramps had to be inserted at points and crossings so that the collector shoes could ride up over the running rails. Drawing McMahon (1899) modified by Author.

The electrical equipment of the C&SLR, including the motors and controls for the locomotives, was contracted to Mather & Platt of Manchester. The locomotive bodies were built by Beyer Peacock, who were actually better known for their steam locomotives. The C&SLR locomotives' equipment consisted of two electric motors, controlled through a hand-operated, rotary power controller carrying traction current through exposed, live contacts connected to the controlling resistors and motors.

There was no driver's safety device (deadman's handle) - it was to be another ten years before it was invented. In any case, a second man was available as he was needed to ride in the cab to assist with coupling and uncoupling.

These locomotives were tiny (Figure 6). With a 10 ft. long body (just over 3 m), they were shorter than the distance between two sets of doors on a modern tube car but they had enough power, just, at 100 h.p. (75 kW) to haul a set of three trailer cars.

For train lighting on the C&SLR, a simple two-core cable was provided down the train at roof level and was connected to three lamps in each car. Connections between cars were along the roof, with sockets and a jumper cable between vehicles. The brake control pipe (later known as the Train Line) was also connected at roof level. The lights were fed directly off the DC traction supply and would reduce to a dull red glow when the line voltage dropped on uphill gradients or at busy times (Lascelles, 1955, p. 17).

4.5 The Waterloo & City Railway

The next electric railway to be opened in London was the Waterloo & City Railway (W&C). This railway is important in this story because it had three major technical distinctions. It was the first tube railway to be allowed cables carrying motor current between cars, it was the first to adopt the duplex floor configuration for its cars that became a standard for London Underground for the next 40 years and it was the first to be built to the American standards adopted for most of the new electric fleets built for the Underground's subsequent electrification.

The W&C was opened in 1898 by the London and South Western Railway as a means of getting their incoming business passengers from their terminus at Waterloo to 'Bank' in the City of London. There were no intermediate stations, just the two termini. It was built with single-track tube tunnels like the C&SLR but with a 12 ft. 1½ in (3.7 m) internal diameter. The line was electrified at 500 V DC, using a centrally positioned third rail. The larger tunnel allowed the 3rd rail to fit centrally under the vehicle couplers instead of being located off-centre as it was on the C&SLR. The voltage was increased to 600 V in 1917.

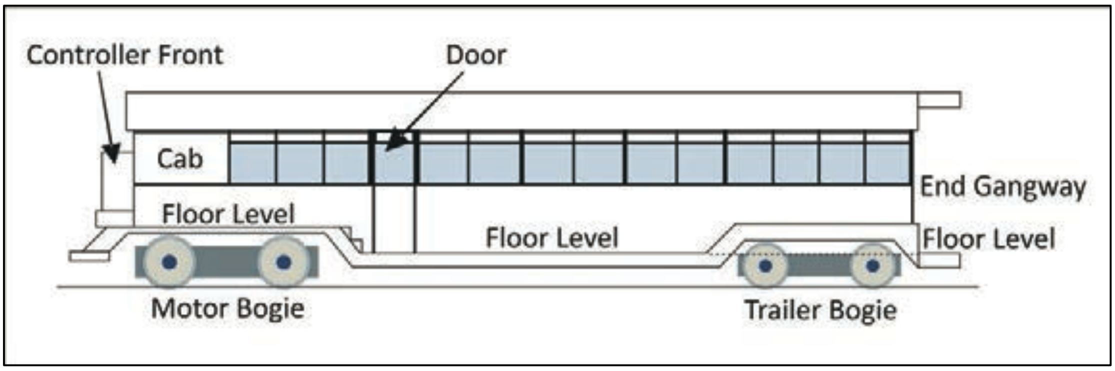


Figure 7: A sketch of a W&C motor car, showing the general layout and split floor arrangement. The floor level was raised over the motor bogie to provide room for the traction motors. The trailer wheels were designed to protrude through openings in the floor that were covered by seats. This was the first example of what became the standard tube motor car design, which lasted for almost 40 years. Drawing by Author from Jenkin (1900).

The electrical equipment was supplied by Siemens Bros., the British arm of the German company. They already had some experience of electric traction. In 1881, they had opened a short tramway in Berlin using 180 V DC electrified running rails. Over the next 15 years they developed electric motors for industry and railway traction and, in 1896, the company equipped a 3.5 mile long underground railway in Budapest (Siemens, 2008).

Figure 8: The motor bogie of a W&C motor car with the cab end of a motor car immediately behind. The current collector shoe can be seen at the front of the bogie. It was similar in design to that of the C&SLR, being a hinged flap. It was mounted on a wooden block attached to the front of the motor case. The huge motors can be seen occupying most of the space between the wheels. The motor armatures were mounted directly on the axles. Photo: Cassier's Magazine, August 1899, p300.

In the W&C contract, Siemens provided the generators for the power station at Waterloo and the electrical equipment for 5 x 4-car trains. The car bodies were built by Jackson & Sharp of Wilmington, Delaware, USA. Separate locomotives were not used. Instead, each train had a motor car at each end with space for 46 seated passengers and a cab with the power controller at the leading end. There were two 56-seat trailer cars between them (Gillam, 2001).

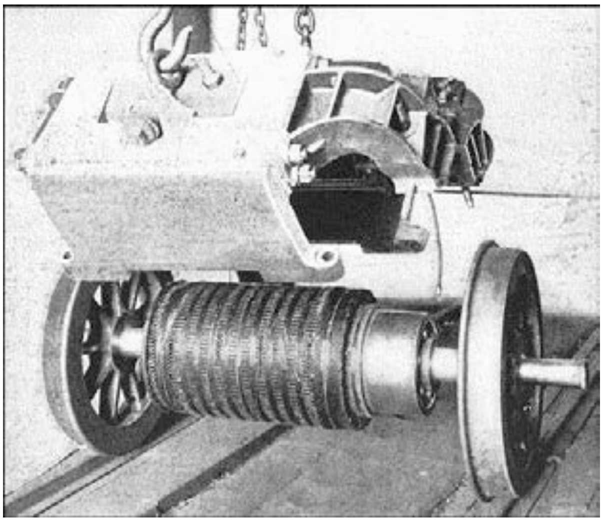


Figure 9: An electric motor with the armature fitted around the axle. The C&SLR, the W&C and the CLR all adopted this design on their original electric trains. It removed the need for expensive and noisy gears but it limited the torque of the motor. This example was used on a C&SLR locomotive. It begs the question as to how difficult it was to fit the case around the armature without damaging the windings. Photo: Cassier's Magazine, August 1899, p353.

Each motor car had a bogie at the leading end with a large, 60 h.p. motor on each axle. Like the C&SLR locomotives, the motors were gearless, the armatures being mounted directly on the axles (Figure 9). The wheels of these bogies were 33 ins (828 mm) in diameter and the car floor was raised from the 1 ft. 10 in (560 mm) level of the main part of the car to 3 ft. 2½ ins (978 mm) to clear these wheels. A small section of this floor was provided with a longitudinal row of three seats either side of the car which passengers could access (doubtless carefully minding their heads in the process) up a pair of steps (Figure 7).

The power controller was large – a roughly 4 ft. cube which sat in the middle of the cab and protruded through the cab front making it look like an old motor lorry (Figure 8). The driver sat on the left hand side and controlled the power through a large wheel linked to a rotating drum inside the controller box. There were eight power positions on the controller.

The rear car was connected electrically to the front car through eleven power cables that ran along the car roofs, so that the driver controlled both cars from the front. The eleven cables were necessary to allow the driver to control the motors at both ends of the train in a series-parallel configuration. This was the first example of a deep level tube railway being allowed to run motor cables between cars. Drawings (Jenkin, 1900) show that the cables were hung in a row over the entrance platforms between cars. They were semi-permanently coupled and suspended from chains attached to the overhanging roof canopies. As the height of the canopy from the floor was 7 ft. 8 ins, it seems it was quite possible for a passenger to touch the cables.

The 500 V DC current was collected by a single shoe attached to the leading edge of the front motor frame and another attached to the leading edge of the trailer bogie. The current rail ran along the centre line of the track and the top of the rail was at the same level as the top of the running rails. To avoid the shoes touching the running rails and causing a direct short circuit, when negotiating points and crossings, wooden ramps were fitted at each location (see Figure 9). These lifted the shoe 1½ ins above the running rail so they could cross without touching it. The shoes were almost 1 ft. wide to allow them to bridge the gap in the ramp where the rail passed through. This seemingly fragile concept seems to have worked and a somewhat similar version was adopted by another new line, the Central London Railway.

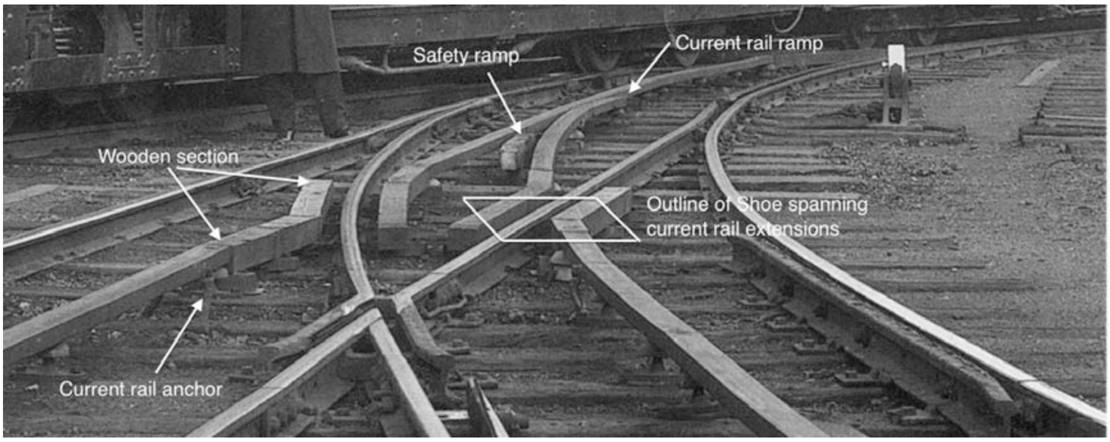


Figure 10: Detail from a photo showing a set of points in the CLR's Wood Lane Depot c. 1925. The current rails have wooden sections added to the ends where rail cross their alignment. The wooden sections allowed the wide shoe to ride over the running rail without touching it. The outline of the shoe is added to demonstrate how it worked. Note also how the ends of the current rails are anchored to the sleepers to prevent them moving out of alignment. The photo also shows how the short, curved section of current rail slopes down where it joins a straight section of rail. This is to prevent the shoe striking a blunt end of rail. The wooden safety ramp between the two joining sections of current rail performs a similar function. LT Museum photo modified by Author.

4.6 The Central London Railway

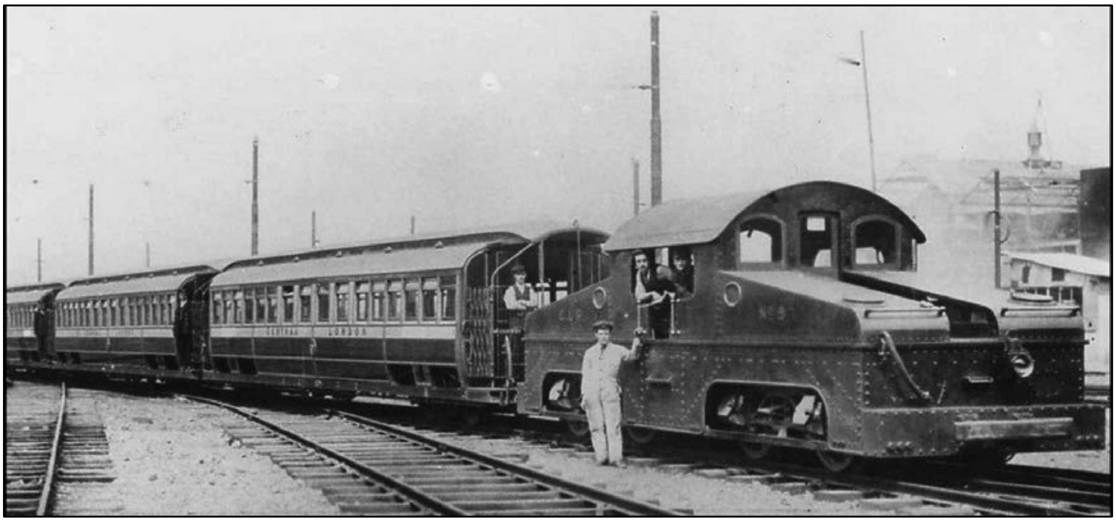


Figure 11: A completed CLR locomotive coupled to a train at Wood Lane depot. There are no current rails. An overhead wire system had been installed over the yard and at least two locomotives are said to have been fitted with trolley poles to allow them to shunt vehicles around the yard. Date believed to be mid-1900. Photo: Collection B.R. Hardy

By the time the Waterloo & City Railway had opened in August 1898, another new tube railway in London was close to completion. This was the Central London Railway (CLR). It opened in July 1900 and ran from the City of London (Bank, as the station was called) to Shepherds Bush – the prime route in London then and still a prime route today.

The CLR learned from C&SLR experience that the tunnels should be a little larger, so they adopted a standard of 11 ft. 8¼ ins on straight track and 12 ft. 5 ins on curves. The diameter narrowed to 11 ft. 6 ins at the entrances to stations where the tunnels were lined with concrete. Like the C&SLR, the CLR adopted locomotive haulage for their trains, so it was necessary to change locomotives at each end of the line. Both lines used the well-tried arrangement at termini where an arriving locomotive was uncoupled from its train and then waited until another locomotive had been coupled at the other end and had taken the train away on its next trip back down the line. The arriving loco was then run clear of the platform where it was held in a short spur to wait to become the departure locomotive for the next train. This was a reasonably efficient solution for the day but it did involve the provision of an additional locomotive for each terminus.

As we have seen, the CLR was electrified with a central positive conductor rail but at 550 V DC (instead of the 500 V of the C&SLR) and set with its top surface 1½ ins higher than that of the running rails like the W&C. The similarity with the W&C

system allowed the Central London to send one of its locomotives there for testing (CLR Board minutes).

With the intention to operate 7-car trains, the CLR locomotives were larger and heavier than the C&SLR machines (Figure 11), weighing 44 tons each, more than four times the weight of the C&SLR locos. They had four gearless motors, so that the unsprung weight was 33 tons. This soon began to cause trouble. Suffice to say here that the locomotives caused such high levels of vibration along the line that they forced the Central London to replace them, as we shall see.

The other Underground lines operating at this time, the District and Metropolitan railways, plus the Circle line, which they shared, were all worked with steam locomotives. The tunnels were dirty, stuffy and full of smoke and steam. Towards the end of the 19th century, there were moves to convert the routes to electric operation but electric traction was then new technology and expensive. The new tube railways had been costly to build and operate and the return for the private investors who invested in them was small. This made financing new electric railways very difficult.

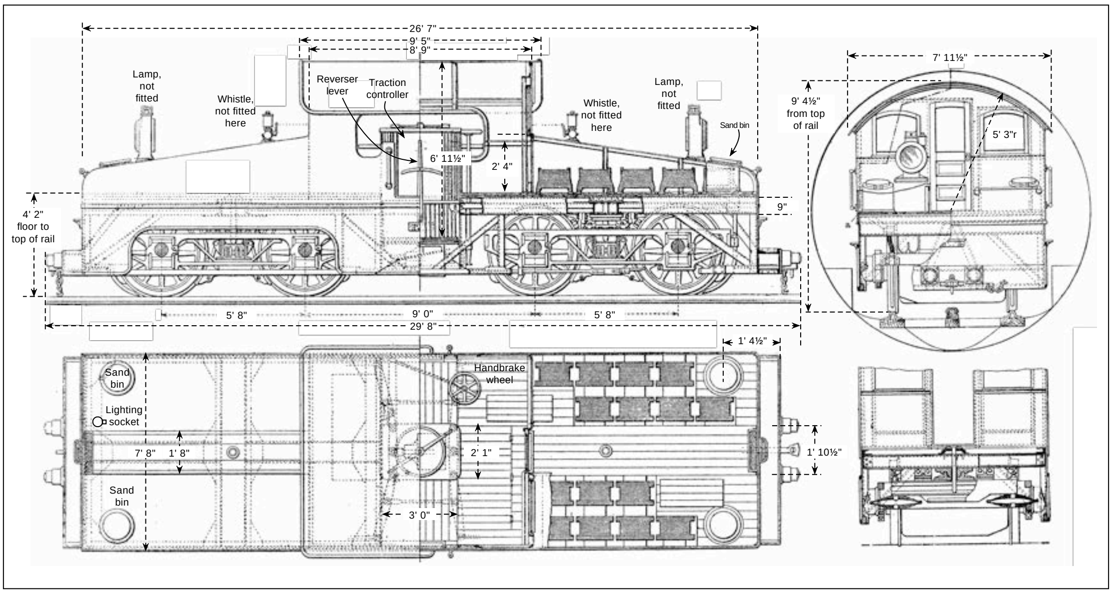


Figure 12: CLR locomotive drawing with known dimensions added. The basic layout is almost as built but the air reservoirs are omitted and the layout of the resistor grids was not as shown here. It is interesting to note that there are no axlebox springs. The lighting socket has been added. One of these was provided at each end of the locomotive. The only indication of how the locomotive was orientated is in the location of the handbrake wheel. This is on the south side of the locomotive. The driver was on the north side. Another item not shown is the steel cover over the twin buffers. With this in place the overall length increased to 29 ft. 11 ins. Drawing from Dawson (1909) modified by Author.

4.7 Discussion

The three pioneer tube railways that had been opened during the 10-year period between 1890 and 1900 provided what appears, at first sight, to have achieved a series of steps forward in terms of technical development. However, closer examination suggests that the Central London Railway took a step backwards in adopting locomotive haulage in 1900 rather than the motor car arrangement introduced on the Waterloo & City in 1898. Why, one could ask, would the obvious advantage of having a train that maximised passenger capacity by using all the vehicles to accommodate passengers and that had a driving cab at each end allowing a quick turnround at the terminals, be abandoned in favour of locomotive haulage with all its disadvantages?

The answer could be to avoid the need to through-wire seven cars but also it could be in the timing. The Act of Parliament authorising the Central London was given Royal Assent in August 1891 (Croome & Jackson 1962) while the W&C was authorised in 1893 (Gillam 2001). The decision to use electric locomotives on the CLR was probably taken quite early on, even though construction of the line did not start until 1896. There does not appear to have been any consideration of any other type of train. They adopted a design based on the electric locomotives of the Baltimore & Ohio Railroad that had been introduced in 1895 (Wilson, & Haram, 1950).

The specification for the W&C trains was issued in March 1897. By this time, electric traction was being introduced on American urban elevated lines, where a ‘locomotive car’ was placed at the end of a set of trailer cars. The first such installation is recorded by Frank J. Sprague (1899) as having been commissioned in May 1895 in Chicago. The locomotive car was a passenger car with electric traction equipment mounted on it. Initially, the leading car was the only one powered but some systems tried a locomotive car at both ends. The one at the rear was dragged as through cables to supply current were not provided. The W&C specification was simply a copy of the locomotive car concept but with power cables connecting front and rear ‘locomotive cars’, although they were never called that in Britain. In terms of innovation, the real progress was to come after 1900 with the introduction of multiple unit control.

4.8 Conclusions

This chapter shows that the status of urban electric traction development in the early 20th Century was still largely experimental. In London, the Central London Railway seems to have taken a step backwards in adopting locomotive haulage in 1900 rather than the motor car arrangement introduced on the Waterloo & City in 1898. The answer is likely to be that the decision to use electric locomotives on the CLR was probably taken before construction of the line began in 1896. There does not appear to have been any consideration of any other type of train. At the time, they did not know of any alternative.

This was new technology, there was little experience to go on and administrators and engineers were still feeling their way, whilst hoping that their investors would get some sort of return on their investment. However, the high cost of the investment came with the expectation of a long asset life. In this expectation, the author concludes that a route to path dependency was already being laid down and that the corporate knowledgebase was gradually being developed within each of the operating companies. At such a critical time in the early development of urban electric traction, combined with the expected long asset life, retention of knowledge to aid future decision making was going to be essential for the future progression of the system.

5 Dreams and Wheelbarrows

5.1 Introduction

This chapter describes the development of multiple unit electric traction on urban railways in the US and London and provides a more detailed background for the case studies in this thesis. The period covered includes the introduction of the multiple unit control system, the design of the nose suspended traction motor and the manoeuvring by some of the companies and people involved in the development phase.

The chapter also shows how, in the early days, the lack of experience in the technology and systems led to some quite serious technical failures and it demonstrates how the rapidly growing expertise of engineers like Sprague, Thomson, Houston and Westinghouse eventually led to success and how this experience was to provide the basis for a reliable and effective railway system.

5.2 More History

Victorian Britain was very conservative in its approach to railway technology, largely because railways were privately financed and owned. The owning companies had shareholders to satisfy and making money from railways was always a precarious business. New technology cost money and, unless it could be seen to make financial sense, no board of directors would allow it on their railway. Some railways readily adopted new technology, like superheating of steam on locomotives to increase efficiency and save coal (Ross, 2004), the use of the electric telegraph for message distribution and the adoption of the Westinghouse air brake to improve stopping performance (Edmonds, 1908). In the late 19th century, new technology known as electricity appeared. Although it was seen to have potential by some, it was generally considered expensive and high risk. Most British railways ignored it.

In the US, many railways also eschewed conversion to electric traction. It was technically difficult at that time to electrify over long distances and the capital costs would have been too high to see a reasonable financial rate of return. However, for short distance, heavily used street tramways however, it was a different story. Most of these used horse-drawn tramcars, and a few were cable operated. Horses were expensive to keep and maintain, requiring at the very least, stabling, water, hay, shoeing and disposal of dung, with vast amounts of labour to provide these facilities. Conversion to electricity showed that operating expenses could be slashed, quoted in one early case as being halved (Clarke, 1899). So it was the street railway operators who first adopted electric traction and it was they who caused it to spread widely in urban transport. Some densely used main lines later adopted electric traction but it was in the field of US urban transport that the early development flourished, so it is there that our story starts.

5.3 A Dream

In America, on 26 July 1897, for one 10 year-old boy a dream came true. He got a brand new train set to play with. This was unusual in those days, since toy trains were rare and expensive but this was no toy. This was a full size train. He was given the controls of the first 6-car electric train to be assembled at the General Electric Company's works in Schenectady, New York and he was allowed to drive the train along the test track in front of the assembled officers and engineers of the Chicago South Side Elevated Railway. The boy's name was Desmond Sprague and he was the son of one Frank Julian Sprague. He was showing off his electrical engineer father's system of multiple unit control, which Dad was trying to sell to the Chicago South Side Elevated (Middleton and Middleton, 2009, p.124).

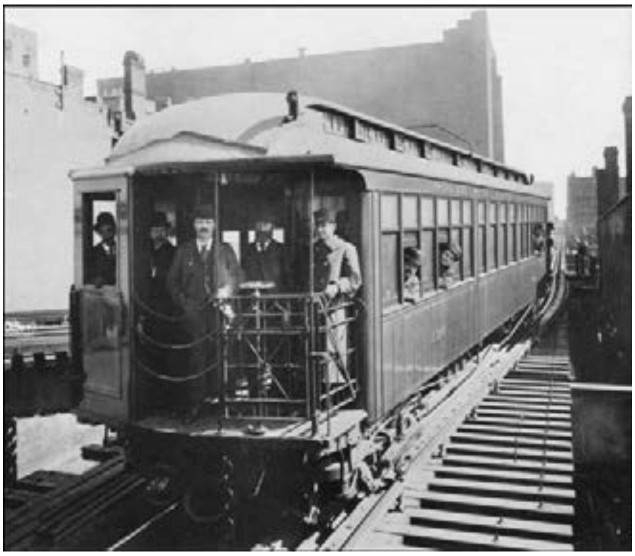


Figure 13: Chicago South Side Elevated car on a demo run in 1898. The driver's cab is the cubicle on the right. Sprague himself can be seen second from the left, standing in the back of the cab. The rest of the riders are company officials and their hangers-on. The general design of the car was to be adopted for the first electric fleets of most of the Underground lines in London. Photo: CERA.

The demonstration was a resounding success and, within twelve months of this demonstration, the whole of the Chicago South Side Elevated system had been converted from steam to electric traction with 120 multiple unit cars. Electric trains, operating under the same principles that their engineers would recognise on electric train fleets today, provided a frequent, high capacity urban transit service and set a new system of railway operation on a path of development that continues to this day. Perhaps it is just as well they did not know then that, over 100 years later in Britain, it would take twelve months just to write the safety management system as part of the process of getting permission to operate the railway, let alone re-equip a whole railway. Sprague (1932, p. 21), who was not troubled by such bureaucracy, proudly noted later that his invention caused the shares of the Elevated company to treble in value.

Sprague's conversion of the Chicago South Side Elevated Railroad to electric traction was not without its troubles. During the early months of 1898, while the newly converted trains were being delivered and tested, one of the cars caught fire. It was quickly found that the cause was electrical and that a large batch of the resistor grids were defective (Sprague, 1932, p. 21). Seventeen of the 20 cars by then delivered had to be taken out of service that day. Suffice to say, teething troubles with new rolling stock are not unique to modern times.

5.4 More Dreams

In the Sprague family, Desmond had not been the only member with a dream. Back in 1881, Sprague senior visited London to attend an electrical exhibition at the Crystal Palace. During his visit, he travelled regularly on the steam-operated lines of the London Underground and he became convinced that here was a system that needed conversion to electric power. He wanted to rid the tunnels of steam and smoke and he had a dream that, one day, electric trains would do the job. He told the story later (Sprague, 1932) that he seriously considered staying on in London just so he could achieve that dream. He did not stay then – electric traction technology had not developed sufficiently to allow its use on railways - but his dream did come true when his multiple unit electric traction system replaced steam in London some 24 years later.

Big Bang Theory

Rather strangely, although Sprague tested his electric motor on the Manhattan Elevated RR, they did not adopt his ideas until early in the 20th century. He told the story (1932) that, during his demonstration on the Manhattan Elevated in 1886, he frightened Jay Gould, the autocratic head of the railroad, when a fuse blew with a loud bang as Sprague was driving the demonstration car. Gould jumped off the car and refused to get back on, believing that he was in danger of his life. Perhaps this was why the Manhattan was the last elevated to convert to electric operation. Sprague later admitted that he had been over enthusiastic in his operation of the master controller and attempted to accelerate too fast, which is why the fuse blew. The idea of an overload relay instead of a fuse came later.

Sprague's invention of the multiple unit system was gradually developed from his involvement first with electric motors and then with lifts. Sprague, who was born in 1857, began his career in 1878 as an engineer in the US navy. His interests were in the field of electricity and, after spending some time at sea and in Europe (including his visit to London), he left the navy in 1883 and, for a few months, worked for Thomas A. Edison on setting up electric light systems[4]. Realising that his real

[4] A useful work on the early history of Edison and his involvement in power distribution systems in cities is "Networks of Power: Electrification in Western Society: 1880-1930, by Thomas P. Hughes, John Hopkins University Press, 1983, Baltimore & London.

interests lay in electric motors and in equipping railways with them, later that year he set up the Sprague Electric Railway & Motor Company. With financial help from Edison's company, he developed a successful constant speed, static electric motor and, by May 1885, Edison was selling the motor under his name. (Middleton and Middleton, 2009)

Sprague was already looking at the electrification of railways, particularly urban railways and, in early 1886, he demonstrated an electrically driven flat car on a section of the steam operated Manhattan Elevated Railroad in New York City. In this instance, Sprague was demonstrating the use of electric motors to drive a train, not multiple unit control, which he was to develop later. At that time, he just wanted to sell motors to urban railway operators.

Although the Manhattan company did not take up the idea of electric traction then, enough people saw it as the future for urban rail transport to enable Sprague to gather a group of investors to put together offers to equip street tramways with electric traction. Their first contract was in Richmond, Virginia, where they had to finance, build and equip a 12-mile long street tramway, complete with power station, overhead wires, track and 40, 2-motor equipped, 4-wheeled tramcars within an heroic 90 days allowed for the whole job.

The contract was signed in May 1887. Sprague (1932, p. 1) said later that his contract had a "superabundance of reckless confidence", especially since his contract to supply 40 motors was roughly equal to the number of electric traction motors that had been built anywhere in the world over the previous 10 years. And, of course, he did not manage to open the line in 90 days. There were lots of technical problems, many, according to Sprague, because of the poor quality of the civil engineering work and Sprague himself caught typhoid fever in the middle of it and spent several weeks in his sick bed followed by several more convalescing.

Sprague lost financially on the Richmond job (amounting to about $1.2 million in today's money) but it was the first complete, long distance, commercially working electric tramway in the world and it led to his company eventually getting over 100 contracts to supply electric traction systems (Middleton and Middleton, 2009, p.83). Because he was already successfully selling electric motors for static industrial use, he had enough money to save him from bankruptcy after the Richmond losses and he had enough for further research and development in electric traction. He did not have the market to himself however, as a new organisation appeared in the eastern US called the Thomson-Houston Company, based in Lynn, Massachusetts. This company, in its British form, was to develop a long and fruitful relationship with London Underground as the British Thomson-Houston Co. Ltd. (BTH).

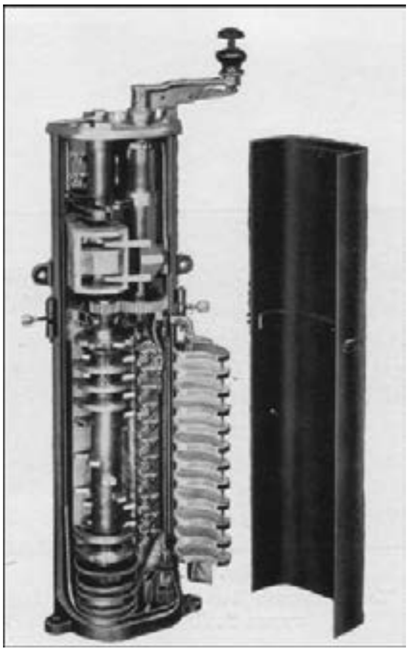


Figure 14: A typical product of BTH – a master controller, as supplied around 1906, for an electric train driving position, with the cover removed to show the control circuit contacts. The key operated reverser switch is on the left (with the key in place) and the controller handle on the right. A spring-loaded button in the handle acted as a 'deadman' facility. The button had to be held down while the controller was in a motoring position. If it was released, the power was switched off and the train brakes applied. Generations of drivers up to the present day would attest that the button, which is still in use on the Underground's battery locomotives, is uncomfortable to hold down for a long time. Author's collection.

5.5 Company Twists and Turns

An interesting change to the corporate relationship between Sprague and Edison took place in 1889. It was to affect the way electric traction was marketed for much of the 20th Century. Thomas Edison formed the Edison General Electric Company to sell electric lamps and DC generating equipment for town lighting and his company also manufactured much of Sprague's motor equipment under contract. Edison had originally financed part of Sprague's company and eventually he got together a consortium with enough stock to allow him to take it over. Up to this time, he had seen Sprague as a partner but now he saw him as a future competitor. The expanded conglomerate began to sell Sprague's designs under the Edison General Electric name. When Sprague discovered that his name had disappeared from his inventions (Sprague, 1932), he decided, apparently in a fit of pique, to drop the traction business and go into electric lift design.

At round this time, another electrical equipment company acquired an interest in railway traction. This was the Westinghouse Electric Company, part of the George Westinghouse empire (he of air brake fame) which was in direct competition with Edison's General Electric, offering AC electricity generation for towns instead of DC. It appears that some of Sprague's engineers, doubtless made redundant by the takeover, went to Westinghouse, taking with them some of the Sprague company's ideas. At Westinghouse, they produced some interesting ideas of their own on electric traction, of which more later (Section 5.7).

Thomson-Houston also developed traction motors and, in Britain, they introduced their electric equipment for tramcars to Leeds in 1891. They already had a foothold in the market here, distributing electrical products from 1886 through a local company called Laing, Wharton and Down (Price-Hughes, 1946, p.8). Edison wanted to take Thomson-Houston out of the market by buying them but he was out-manoeuvred by their CEO, Charles Coffin. In 1892, Edison's GE company was absorbed by Thomson-Houston and Edison's name was dropped from the title. The new organisation was simply called General Electric (GE) and Coffin became CEO.

In Britain, so that they could expand their market, the enlarged GE put additional capital into Laing, Wharton and Down in 1896 and renamed it British Thomson-Houston (BTH). During almost the whole of the 20th century, BTH and its successors, would be the London Underground's principal traction equipment supplier.

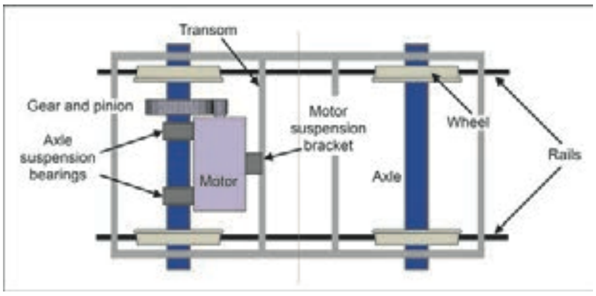


Figure 15: Simplified diagram of Sprague's system of motor mounting in a bogie frame. Only one motor is shown for clarity; usually both axles were motored. He called it a 'wheelbarrow' suspension. Later it became known as a 'nose suspended motor' arrangement, the 'nose' being the motor suspension bracket that rested on the bogie transom. The clever thing about this arrangement was that it allowed the weight of the motor to be distributed between the bogie frame and the axle while keeping the pinion and gearwheel in mesh, regardless of the movement of the axle relative to the bogie frame. Drawing: Author.

5.6 Wheelbarrows

Sprague's demonstration in Manhattan of electric motors driving a rail car saw the first example of what eventually became the standard arrangement for a motor bogie for electric railway traction around the world. It was to become known as the 'nose suspended motor' and, since it used a 3-point suspension principle, Sprague likened it to a wheelbarrow (Figure 15).

The traditional bogie frame consists of two side frame pieces and two headstocks forming a box structure. To add strength, a pair of cross members, called transoms, are added. Sprague installed his motor between the transom and the wheelset with a 3-point suspension – two points on the axle and one on the transom. A schematic arrangement is shown in Figure 15 above (Hutchinson, 1899, p.338).

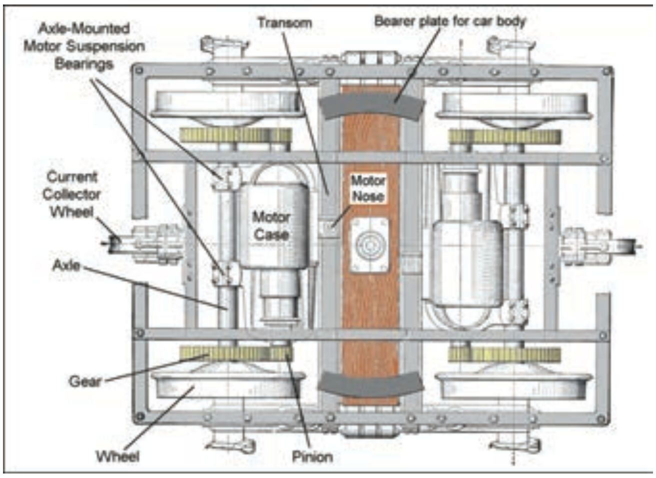


Figure 16: A detailed drawing of the original Sprague motor bogie adapted by the author from a graphic in Cassier's Magazine, August 1899. The bogie was used for the original Manhattan experimental car in 1886. It shows the 3-point motor suspension known as 'nose suspension'. It also has gear drives at both ends of the motor. This was soon found to be unnecessary and later models had the drive at one end only. Drawing modified by Author.

Sprague's idea was to hang the motor between the transom and the axle, with two bearings on the axle carrying part of the motor weight and a third fixed to the transom so that the bogie frame carried some of the weight. This was Sprague's 'wheelbarrow' with its three mounting points; one in front and two at the back. The one at the transom end was called the 'nose' and in the early days it was usually fitted with springs to further reduce vibration.

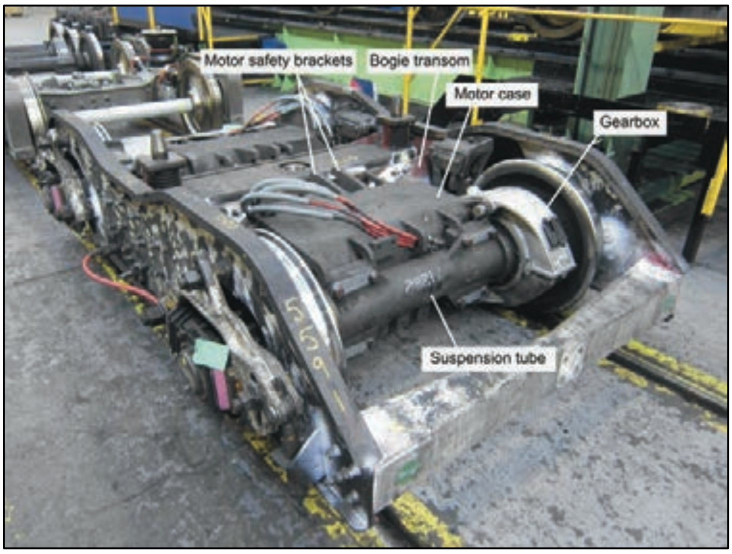


Figure 17: A motor bogie from a 1972 Tube Stock car, showing the nose suspended motor fitted into the bogie frame. The motor case is bolted, on one side, to a suspension tube mounted round the axle and, on the other side, to the bogie transom. Additional safety brackets are provided on the transom side. The motor drives the axle through the gearbox at the end of the suspension tube. Photo: Author.

The drive system was a simple pinion, driven by the motor, meshing with a gear added to the axle. In Sprague's original design (Figure 16), there was a gear/pinion set on both sides of the motor but it was soon reduced to one set and this remains the norm.

Sprague's drawings of his 1886 Manhattan bogie (Figure 16) also show current collectors mounted roughly where London Underground negative shoes are today, hung off the bogie headstock. A strange feature of the current collectors was that they were in the form of wheels, like the trolley wheels used on tramcars but rather larger. They were also spring-loaded to provide good contact with the centrally positioned current rail.

Many years later, in 1932 just two years before his death, Sprague (1932) wrote a brief account of his Manhattan electric traction trial and in it he mentions, almost in passing, that his system incorporated regenerative braking and that later in the trials he installed new motors with interpoles in an attempt to reduce arcing on the commutator, a feature which did not appear on the London Underground until 1914 (Bruce 1988, p.46).

The design of interpoles proved troublesome at first but it was eventually developed sufficiently to see their introduction on motors provided for the 1000V DC Cologne to Bonn railway in 1905 and in 1907 the US was marketing 600V motors with interpoles (Pannell, 1916, p. 453). They soon became standard in new motors. Regeneration was more difficult to activate with the lightweight electro-mechanical controller used in the Chicago installation and it was abandoned.

5.7 Lift Control to MU Control

Sprague's diversion into the lift business in 1889, under the name Sprague Electric Elevator Company, was to offer electric motors for lifts to replace the steam or hydraulic power that was used for lifts in those days. Part of his design involved a way of controlling the electric motor mounted at the top of the lift shaft from inside the lift car. He adopted a form of remote control, using a relay. When a switch inside the car was closed, a current passed up a cable to an electro-magnetically operated switch (effectively a solenoid) in the machine room. This closed a set of contacts in the power circuit and activated the power for the motor to drive the lift. In this way, the high power required to drive the lift did not have to pass down a heavy cable to the controller inside the car. The controller also used much less power in a separate circuit. Sprague developed his system further into two remote controllers, one in the lift car and one on the basement landing. It was first tried in the Postal Telegraph building in New York City in 1894 (Sprague, 1899).

The lift design was a success and led Sprague, in 1895, to see if the idea could be applied to electric trains. He called it 'multiple unit' control. He knew that there was scope for the system on American urban elevated railways, which then operated up to four cars per train.

Some of the steam operated elevated railways already operating in New York and Chicago were looking at converting to electric traction and Sprague was invited to act as consulting engineer to one of them, the Chicago South Side Elevated. For the conversion, the South Side expected to have locomotive cars hauling trailers, like the other lines, but Sprague took the opportunity to propose his new multiple unit system. It offered benefits in allowing more than one power car in the train, with the opportunity for longer and faster trains, and it reduced the turnround time by eliminating the uncoupling/coupling procedure.

By this time, Sprague seems to have made up with GE and he got friends there to help him with trials and to let him use their test track at Schenectady. As we have seen, his success with the tests led to the complete conversion of the South Side line. What is curious about this story is that GE were actually bidding for the job of electrifying the line but they were not aware that Sprague, who was supposed to be the consulting engineer for the South Side, was also bidding against them to supply his MU system. They were not happy when he won.

5.8 The First Multiple Unit System

Sprague initially equipped 120 former steam-hauled South Side Elevated cars with his system (Dalzell, 2010, p.161). The cars were typical US-style passenger cars with gated open entrance platforms at the ends and 'clear storey' (later clerestory) roofs. All became motor cars, each with a single motor bogie at one end and a trailer bogie at the other end. Driving positions were provided at both ends of every car. This was a legacy of the original tram and locomotive car design, where the car had to have driving controls at both ends to avoid the use of a turntable or loop. To change direction, the driver just had to change ends.

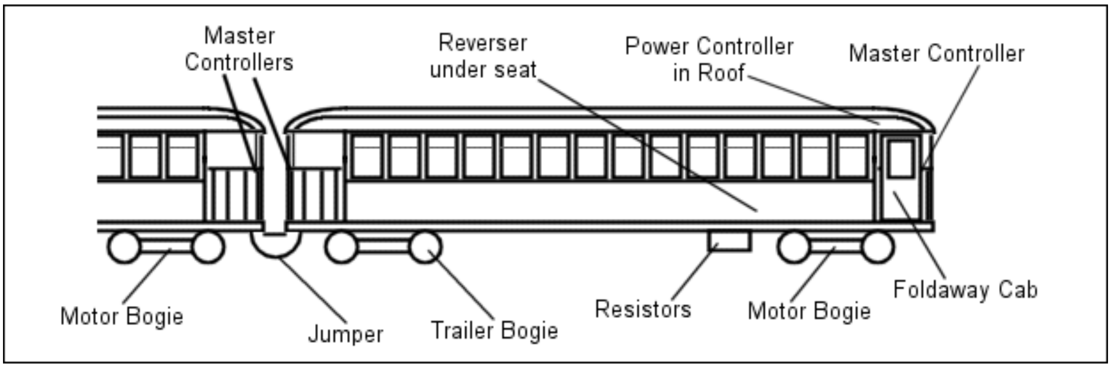


Figure 18: Schematic of the layout of Sprague-equipped cars used on the Chicago South Side Elevated RR in 1898. All cars were motor cars with one motor bogie and two master controllers. Cabs were one third of the width of the car and could be folded away when not in use. Drawing: Author.

The layout of Sprague's system was rather different from what we see today. Today, for safety's sake, all the 600 V equipment is below the floor. On Sprague's system, the power controller was fitted in the cab roof. It had a rotating drum carrying the 600 V switches that controlled the resistances in the motor circuit. The drum was turned by a small electric 'pilot' motor whose speed depended on the current passing through the main motor circuits. 'Notching up' to full power was therefore automatic[5]. There were three positions on the master controller, basically the same as the 'Inch' (very slow), 'Series' and 'Parallel' still seen today on the Underground's pre-1992 trains.

The driver's controls were mounted behind a one-third width wooden screen on the right hand side of the gated entrance platform (Figure 18). The controls were at waist height under a windscreen. A side screen, with a window, unfolded to provide an outside wall. This elaborate setup was a direct result of having controls on each end of every car but with the additional need to use the platform for passenger loading/unloading.

Because controls were provided on every entrance platform, they had to be tamper-proof, so both master controller and brake handles were removable. Later, master controllers were isolated by removable keys and had their handles fixed but the driver always took the brake handle with him. Some were personalised by their owners with elaborately decorated handles. The District imported the idea from the US for its 1903-5 electric stocks but it did not survive for long and fixed controller and brake handles became the norm on the Underground. Only the master controller keys were removable.

5.9 Multiple Unit Control

As in Sprague's lift control, the multiple unit system used a set of low voltage wires to connect the driving positions in the cabs to the control gear of the higher current traction equipment on the train. In the early examples, the current for the control circuits was taken off the 600 V DC third rail supply and the voltage reduced by resistors. The leading 'master' controller was connected by a switch (the 'control switch') to the wires running along the full length of the train. Other controllers were isolated by opening the control switch, which was later to become key operated – the 'control key'. The wires were grouped together in a multi-core cable and, to allow for vehicle movement through suspension and curves and to permit simple uncoupling, they had removable flexible connections between cars called 'jumpers' (**Error!**

[5] The term 'notching up' comes from steam locomotive control, where the valve gear is set by a lever mounted in a notched frame to latch it in the required position. To increase power, the locomotive is said to be "notched up". The phrase was carried over to electric traction.

Reference source not found.). Sprague's original M.U. system had a five wire control cable; later versions had nine or ten wires when automatic acceleration was dropped. The basic principles of the system remain to this day. Jumpers were fitted into sockets at the car ends and are usually duplicated either side of the central coupler in case a car got turned. This became a problem for the tube lines in London because of their low floor height and led to some complex schemes over the years.

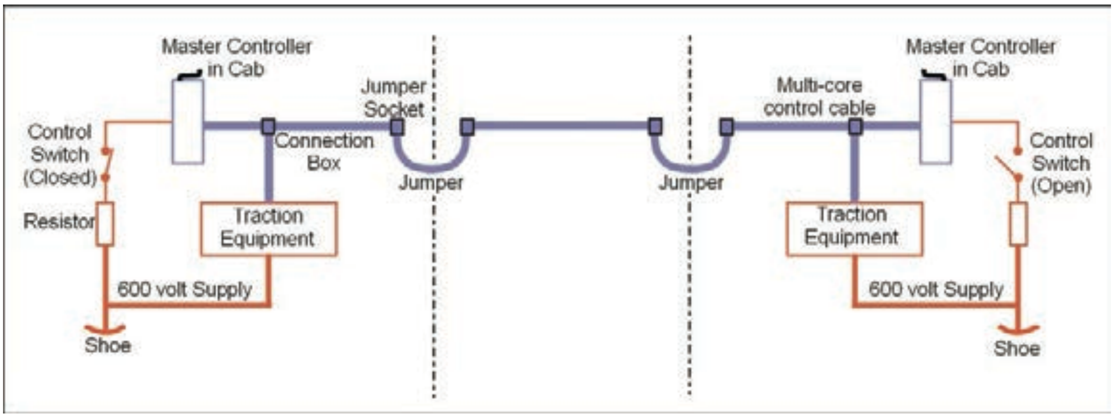


Figure 19: Schematic showing the basics of the multiple unit layout on a 3-car train with two motor cars and a trailer. In reality, up to six trailers could be coupled between the motor cars. Both motor cars collect 600 V DC from the track to supply their traction equipment but only the leading master controller has a low voltage supply through the closed control switch. This controller sends signals down the multi-core control cable to the traction equipment switches on each motor car. The cable is connected between cars by a jumper. Drawing: Author.

5.10 Series-Parallel Control

A feature of Sprague's traction system was series-parallel control of motors. On one of the few occasions when he admitted that something in the railway traction business was not one of his ideas, Sprague (1932) said that series-parallel control (which he used at Richmond, Virginia) was John Hopkinson's idea. Looking back now, this seems strange because, although Hopkinson was the consulting engineer for the C&SLR, he did not use series-parallel control. His original locomotive design had two traction motors permanently wired in series.

Series-parallel control was to become a fundamental feature of the traction system used on the Underground (and many other DC electric railways) until the introduction of electronic power control in the 1990s. It was introduced on the C&SLR in 1898 (on Locomotive No. 18) and became standard thereafter. It was only superseded in the 1990s when modern electronics allowed the introduction of the brushless AC motor, with its simpler design and easier maintenance, driven from a DC supply through an on-board inverter.

5.11 Summary

In this chapter, we have seen the development of the multiple unit system and the nose suspended motor. With the basic multiple unit traction control setup that Sprague designed for Chicago in 1898, we have all the elements in place for multiple unit traction that have remained, in principle, to this day. Not confined to traction equipment, the same idea was adopted on trains for door control, lighting, heating, ventilation, compressed air, brakes and communications, although not all were done at that time. Put in modern language, we can say that a low voltage, remote control system using a hard-wired distribution network is connected to high voltage or remote equipment packages. Connections to the man-machine interface can be tapped into the network at selected locations.

In the 10-year period between 1888, when a viable tramcar system was introduced, and 1898, when multiple unit traction arrived in Chicago, significant progress was seen in electric traction. In particular, motor power increased from the 7 h.p. of the Richmond tram motor to the 50 h.p. used in Chicago, motor efficiency was improved when gearing became a viable option and multiple unit control replaced single car control, allowing power requirements to be matched with variable train lengths.

5.12 Conclusions

It this chapter, it is shown that a number of lessons were learned during the early development of electric traction for urban public transport in the US and London. The first lesson was, be prepared for things to go wrong with new systems and be prepared to cope with them, as in the case of the defective resistors in Chicago. In addition, 'Don't run before you can walk' might have been applied to Sprague's ideas for both regenerative braking and automatic acceleration. He knew they were possible but the lightweight electro-mechanical control systems he designed were not refined enough to allow reliable, in-service operation. In the example of motor/axle gearing, a single gear/pinion proved to be sufficient rather than the two he originally designed. And the wheel-based current collection system, whilst working fine on overhead wire trolley systems, didn't last for 3rd rail railway operation. It is likely that this was due to the higher currents needed for trains causing deterioration of the wheel bearings. In addition, the problems with the traction resistors on the initial Chicago electric cars showed that a good system can be let down by poor materials.

Perhaps the single most important lesson learned was that new ideas might seem to solve a problem but that the engineer must be prepared to adapt his design to suit service conditions or even, in extreme cases like regeneration, put it to one side until practical technology has caught up with the theory. In parallel, clients must expect new systems to require a shakedown period and appropriate time and cost should be allocated for it. The pioneer engineers and operators of the London Underground were gaining from their experience as their system developed. This is still occurring today as new systems are introduced and allowance in future project plans should be made for it.

6 Electric Traction in London

6.1 Introduction

This chapter describes the development of the electric traction systems applied to the London Underground from the major line electrification projects of the 1905-7 period to the present day. It demonstrates the pattern of technical and operational development and shows the path dependency that the system adopted over the years. It includes the traction current supply system as well as the application of technology to trains.

In this chapter, the author shows the path that developed in London as electric traction was applied to the new and existing urban railways on a large scale. In most cases, the introduction was a success because the technology has already been tried out in America and it was being installed in London by experienced, mostly American, engineers. Failure occurred with the systems that were new and not fully understood, even by the suppliers, as in the case of the Central London Railway.

During this period, valuable lessons were learned that are just as valid today as they were then. It was learned that railway equipment is expensive, has a long life and must be reliable. It also showed, more than once, that even prototyping does not always prove a system.

6.2 Problems of Electrification

In London, the opening of the new tube lines with electric traction in the late 19th century showed what could be done with modern technology. It also showed up the steam operated Metropolitan and District railways as old-fashioned and behind the times. When the third of the new tube lines, the Central London, opened in 1900 between Shepherds Bush and the Bank, it was in direct competition with the Metropolitan's route to Moorgate and District's route to Mansion House, which is a short walk from the Bank. The District, almost always being in a bad way financially, rarely ever paid a dividend on its ordinary shares. Off-peak traffic was very light. Apart from some commuter traffic from the western suburbs, the fortunes of the railway seem to have rested on the popularity or otherwise of the various exhibitions which were staged on District land at Earls Court. Alexander Edmonds, in his history of the District (Edmunds, 1908), describes how the income fluctuated during the final years of the 19th century in accordance with the levels of exhibition traffic. It was a precarious railway company indeed that relied on showmanship by others for its survival.

In spite of, or perhaps because of its financial position, the District's management was forced to get into negotiations with the Metropolitan Railway over how things might be improved. Electrification was obviously the way forward and, with their joint operation of the Circle, they had to choose the same system. With the long-standing rivalry that existed between the two companies, they must have struggled to get through the animosity to decide how to tackle the problem. Still, eventually they did and they agreed, in May 1898, to try out an experimental installation of electric traction between High Street Kensington and Earls Court.

6.3 Siemens Equipment

The contract for the Earls Court trial was eventually given to Siemens. The traction current for the joint experiment was supplied at 500 V DC, from a specially built power station at Warwick Road (near Earls Court), to pairs of current rails (one positive and one negative) located on the track. Both rails were positioned outside the running rails in the style later adopted by the Great Northern & City Railway but the arrangement was never used on the rest of the Underground network (see box, below).

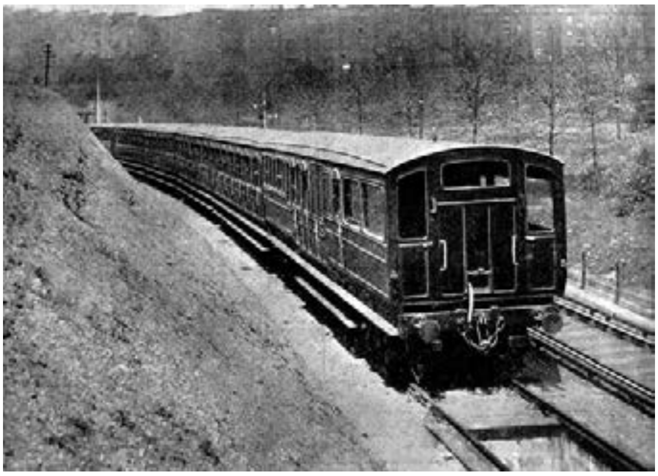


Figure 20: The Metropolitan and District Railways' jointly owned experimental electric train stabled in a siding next to the eastbound track between Earls Court and High Street in 1900. This whole area is now built over. The outside conductor rails can be seen on either side of the adjacent eastbound track. One was positive, the other negative. This arrangement was abandoned because it would have been unworkable on the Circle. Photo: The Electrician, (1900).

A special 6-coach train was ordered in May 1899 from Brown Marshall & Co. of Saltley, Birmingham (later absorbed into the group that eventually became Metro-Cammell), which was delivered late in 1899 to the District's depot at Lillie Bridge. Trial running started early in December 1899 and continued spasmodically up to 21st May 1900, when public operation began. The District charged a fare of one shilling - 5p in decimal money but actually the equivalent of £4 today. Naturally, the train ran practically empty, since the ordinary fare was about 20% of that, so it only took the District a week to drop the special fare. Even so, the train never did 'pay its working expenses', as reported at the time (Edmonds, 1908, p. 178) – hardly surprising, since it was a high-tech experiment over a very short piece of line. We might wonder today why anyone thought it would give a meaningful assessment of running costs in the first place.

The train was formed with a motor coach at each end of a set of four trailer coaches, all vehicles being based on traditional British compartment style coaches with 'slam doors'. The motor coaches were like the US elevated style 'locomotive car', the leading coach hauling the whole train without assistance from the other motor coach at the rear, which was towed like a trailer. There was no though control and no power connections to the rear motors from the front but there was a pair of 'bus lines' connecting the 14 sets of collector shoes along the train. This reduced the risk of the train getting 'gapped', i.e. stalled at the breaks in the current rails (necessary at points and crossings) due to loss of contact between the shoes and the current rails (The Electrician, 1900). The motor coaches had a control compartment at the leading end with a power controller operated by a large hand-wheel. The driver sat beside it, as on the W&C.

The Siemens motors were very large so the driving wheels had to be 4 ft. (1219 mm) in diameter compared with the usual 3 ft. (1067 mm) diameter for coach wheels. In fact, the motors were so large that the motor coach floors had to be raised about 6 in (152 mm) higher than normal over the bogies at each end of the vehicle. For passengers using these coaches, access doors were restricted to the central part of the body and, inside, the floors sloped upwards to the seats provided over the bogies. The seats were longitudinal in these areas (The Electrician, 1900, p.163).

Outside Conductor Rails

Having two separate conductor rails, one on either side of the running rails, would have presented a difficulty if it had been used for trains going round the Circle. Let us say the positive rail was on the north/west side of the track between Earls Court and High Street. If this was continued on round the Circle via Baker Street and back on to the District at Tower Hill, the positive rail would now be on the south side. Travelling on to Earls Court, the positive rail would now be on the other side of the track compared with when the journey started. One might wonder how long it took to realise this. For the main electrification, the District & Metropolitan used a 4-rail system with the positive rail on the outside of the track (swapped from one side to the other as necessary) and the negative rail in the middle. This was also adopted later on the tube lines.

The trains were provided with the Westinghouse air brake and an electrically driven compressor was fitted in each motor car to supply it, the sanding equipment and the whistle. The Westinghouse was already the brake used by the District and it was to become the standard brake of the Underground railways in London and, in spite of the fact that the Metropolitan used the vacuum brake on its steam trains, it too adopted the air brake on most of its electric trains (Metropolitan Railway, 1933, pp. 3-33).

6.4 Next Steps

The experimental service went on through the summer of 1900, finally being wrapped up on 6th November, when the train was withdrawn. Even while the experiment was still going on, the joint committee asked for a report into "*the whole question*", as Alexander Edmunds (1908, p. 179) put it, of electrification. They were soon told they should electrify "*the whole system*" and that they would need "*two or more*" new trains on the "*multiple unit*" system for the Inner Circle and some electric locomotives to haul the existing coaches on the branches (Edmunds, 1908, p. 179). It is interesting to note that they knew about Sprague's multiple unit system as early as the summer of 1900 and that they thought it was the way to go.

The experimental train was still running when, on 3rd August 1900, nine different firms were invited to tender for the electrification of the Circle. It is an instructive thought that the tenders were due to be returned by 1st December in the same year, while our modern procurement processes seem to demand six months just to pre-qualify, let alone submit a bid. No wonder our railways are now so expensive.

Two suppliers for the electrification project became qualified as what we would call today 'preferred bidders' –BTH and Ganz & Co. of Hungary. BTH proposed the DC 3rd rail system to become familiar across the world in many urban railway systems and with earlier versions already in place on the W&C, Central London and C&SL railways, while Ganz offered a 3000-volt, 3 phase AC system requiring three conductors - twin overhead wires for two phases and the running rails for the third phase. The electrification committee came down in favour of Ganz, without a doubt because it was the cheapest offer but almost certainly against the advice of any sane electrical engineer of the time (Edmunds, 1908, p.180). Regardless of it being untried and untested, just the electrical clearances required for the twin overhead lines in the tunnels of the Circle should have disqualified it.

In the event, the whole question of the choice of electrical system was turned on its head by the inability of the District Railway to raise enough capital in London to pay for it and having to turn to the US for it, where an urban railway financier, Charles Tyson Yerkes was persuaded to finance both the District's electrification and the building of three new tube lines. He set up a company, the Underground Electric Railways of London Ltd. (UERL) to electrify the District (Edmonds, 1908, p189).

Yerkes brought a technical advisor to Britain, one James Russell Chapman, who had considerable experience of setting up electric railways in the US, notably in Chicago. Chapman quickly realised the weaknesses of the Ganz system and set his mind in favour of something akin to the BTH proposal, already tried and tested in the US and, as we have seen, adopted by the pioneer tube railways in London. This was in direct opposition to the joint electrification committee's choice of Ganz and it precipitated months of argument between the District and Metropolitan, which ended up with them going to arbitration. The arbitrator's decision, which was in favour of the

District's DC system, was made in December 1901. An interesting hint in Edmunds' history (1908, p. 199) suggests that, as is often the way in such things, the Metropolitan only fought the District over the DC proposal because Ganz were paying their legal costs.

6.5 Central London Conversion

Initially, the Central London Railway (CLR) was a great success. Traffic levels were robust from the line's opening in July 1900, with up to 140,000 passenger trips a day but there were the inevitable teething troubles. Various reports at the time suggested that the locomotives were prone to derailment and there were problems with the traction supply system that required modifications to be carried out. However, the most serious issue for the railway was vibration. (Wilson & Haram, 1950, pp. 24-25)

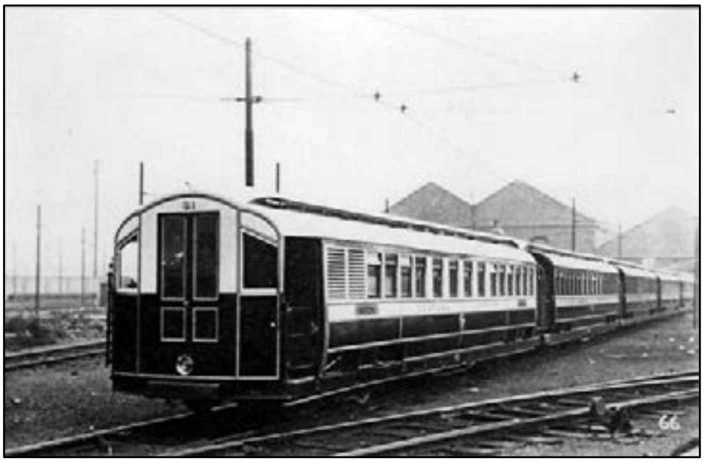


Figure 21: The Central London Railway's first 6-car, experimental multiple unit train at Wood Lane Depot in the spring of 1901, when trials with the new system were started. The driving cab was added to an existing car in the form of a new front screen with a full width roof over the original end platform. It had no side doors, just a gate on each side. The car is facing west and the driving position is on the North side of the train (the left hand side as we look at it), the same as the locomotives. The driving position at the other end of the train was on the same side. (Collection B.R. Hardy)

Soon after the line opened, a number of property occupiers along the Central London's route began to complain of vibration when trains passed underneath. The problem seems to have become public knowledge about three months after opening. A number of letters to 'The Times' in early December 1900 suggest that reports had been around for several weeks by then and subsequent investigation was to reveal that the evolution of the problem was gradual. It was found to be due to the high unsprung weight on the loco axles and the damage it did to the joints of the shallow rails laid to compensate for the oversize of the locomotives as originally designed. The rail joint damage built up until it became very noticeable (Mallock, 1902, p.4).

There is no doubt that the Central London knew that there was going to be a problem before the opening of the line. The residents in various locations had already become aware of the passing of trains by the vibration they had heard during the several months of testing. Wilson & Haram (1950, p. 24) suggest that complaints started "*towards the end of 1900*". The CLR must have known that the unsprung weight of the gearless motors was far too high and they also knew by the time of the line's opening that geared designs were now available and workable. That they were worried by the signs and that they were pretty sure that they knew what the solution should be, was clearly signalled by the decision to order some new bogies with geared motors and improved suspension. They ordered enough to equip three locomotives. Quite when this happened is not clear but it must have been before the end of 1900. A reverse process of the sequence, suggests that testing with the new bogies must have started in the spring of 1901 to give time for assessing the results and preparing conclusions before publication. To get the bogies manufactured and ready, the order must have been placed around six months earlier, say October 1900.

At around the same time the new bogies were ordered, the Central London decided to convert two of their trains to multiple unit traction. The conversion involved equipping the train with motor bogies and geared motors and providing new control equipment. For the two trains, they needed four motor cars, each one to be equipped with a motor bogie carrying two motors plus a set of multiple unit (MU) control equipment.

A trial of the multiple unit system was carried out early in 1901 using four existing passenger cars which were converted to driving motor cars (Figure 21). They were modified by adding a driving position and motor bogie at one end, with the power and control equipment in a small compartment above the bogie (Dawson, 1909, 347). The multiple-unit equipment to Sprague's patents was supplied by GE's subsidiary company in Britain, British Thompson-Houston. They used a new version known as 'Type M' control. This replaced the electric pilot motor and drum controller of the Chicago South Side installation with groups of individual switches called contactors. Each contactor was operated by an electro-magnet.

The contactor system was necessary because the small switches in Sprague's original drum controller could not carry the higher currents being demanded by the larger motors arriving on the traction scene. The CLR experimental motors at 100hp were almost twice the size of the South Side design. Each motor car had two of these motors driving 3ft diameter wheels (Parshall, Parry & Casson, 1903, p. 29).

The individual contactors were each fitted with a 'blow-out' coil, wrapped round an iron core, which provided a magnetic field to extinguish the arc caused by the opening of the contactor under load. This action was accompanied by a loud 'plop' as the contactor opened. The use of individual contactors also allowed better insulation than was possible between the small drum controller contacts.

The new equipment also lost the automatically controlled acceleration of the original Sprague system. The pilot motor was slow to respond and the system was prone to failure. With the Type M equipment, each resistance cut-out step was now controlled manually by the movement of the driver's master controller in the cab. Instead of three operating positions, the Type M controller had ten. The driver had to be careful to judge the step from one position to the next in case he tried while the current flow was still too high and he ended up rupturing the main fuse. In later versions of this equipment, a circuit breaker was provided to detect overloads before the fuse blew.

The CLR's experimental motor cars were similar in layout to the W&C motor cars, having a raised floor over the bogie at the driving end, but all the electrical equipment was mounted on this floor behind the cab instead of the W&C arrangement where much of it was beside the driver. The equipment area behind the driver later became known as the 'switch compartment'. In the first two cars, it was limited to converting some seat space into space for equipment. Only 4ft 9ins in length was available and in this they had to provide a central gangway, with the resistors, contactors, control rheostats, an air compressor and two small air reservoirs for the brakes crammed into the space either side. Things were so difficult to get at that photographs of the second two experimental cars show that they were built with enlarged switch compartments but at the expense of eight seats.

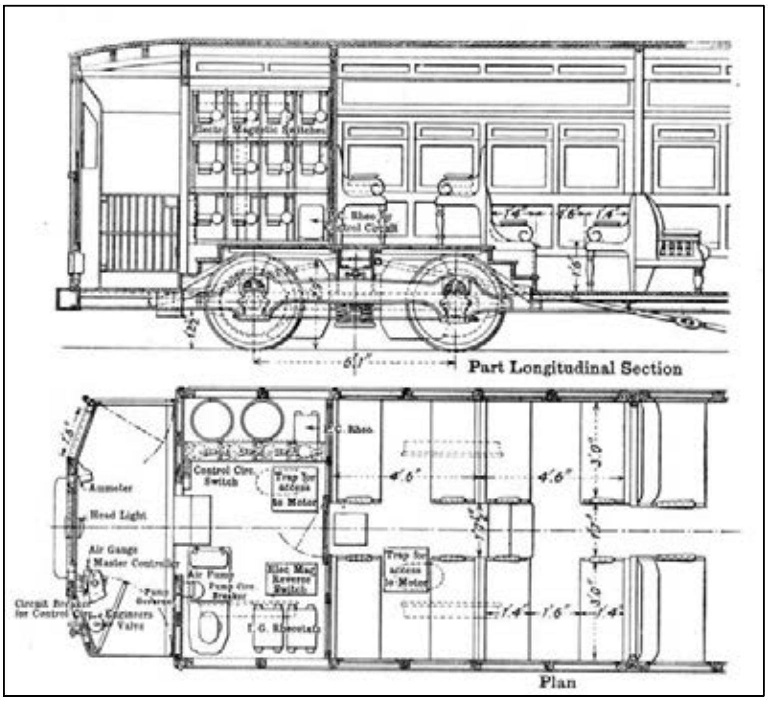


Figure 22: A drawing of the first CLR trailer car converted in 1901 as a motor car for multiple unit experiments. The floor over the motor bogie was raised, an idea taken from the 1890-built C&SLR locomotives. The length of the cab and equipment section was only 8ft 3ins. This was increased to 12ft 3ins for the last two of the four cars converted. Source: Dawson (1909, p.347).

After some experiments with shorter trains, the converted motor cars were formed with one at each end of a set of four existing trailer cars to make up a 6-car train. The trailers were fitted with multi-core control cables to provide the multiple-unit connection between the two motor cars. Two such trains were tried in a series of tests in the summer of 1901 (Mallock, 1902, p.5) and it was found they reduced the vibration problems to such a degree that the company was quickly convinced that the locos would have to go. They therefore ordered 64 new motor cars (Parshall, Parry & Casson, 1903, p. 32) with BTH m-u equipment and GE66 125hp geared traction motors with nose suspension and put them into service gradually from early in 1903. The Central London thus became the first British railway to adopt the Sprague multiple unit system.

In terms of a cost benefit analysis, the re-equipment of the Central London probably broke even. Notwithstanding the reduction in vibration and its associated compensation risks, the adoption of multiple unit control allowed capacity to be increased by 16% because of the reduction in terminal operation time and there was a reduction in journey time achieved by the introduction of motors with a 25% increase in power (Parshall et al, 1903). It was also obvious that re-equipping the existing locomotives with new bogies and motors was not going to be much cheaper than adding a new bogie to each end of the existing trains. Doing this and including them with new motor car bodies increased the size of the passenger fleet so that, following the conversion, 32 multiple unit trains were available for service instead of the 28 locomotive hauled trains.

6.6 Westinghouse Arrives

In 1899, the British Westinghouse Electric and Manufacturing Company was set up in Britain with premises in Trafford Park, Manchester (Dummelow, 1949, p3.). The company was a subsidiary of the US-based Westinghouse Electric and Manufacturing Company, with George Westinghouse as president. Westinghouse himself was no slouch commercially and he had seen the potential for electric traction on railways. With some of Sprague's former engineers in his employ, he went to work looking at multiple unit systems. He knew that Sprague's ideas on m-u traction were sound and that this was likely to provide a substantial market. He started a few years behind Sprague but he soon caught up (getting sued by Sprague (1932) for patent infringements in the process) and it was 1902 when he first sold his multiple unit system in the UK - to the Mersey Railway in Liverpool (The Electrician, April 24th 1903, p. 8.). He also offered the system to both the District and Metropolitan Railways in London. The District took a trial set, while the Metropolitan ordered enough equipment, initially sight unseen, for its first two batches of electric stock.

6.7 The British Westinghouse (BW) System

The original Westinghouse m-u equipment was electro-pneumatic. It is described in detail by Dawson (1909, p. 332-333). It used a drum controller operated by compressed air pistons. The pistons turned the drum. They were controlled by electric valves operated remotely by contacts in the driver's master controller. Forward and reverse selection was also electro-pneumatically operated. Acceleration was automatic, the progress of the resistance switching being regulated by a 'limit switch'. All the driver had to do was select one of three master controller positions as follows:

1. Switching – all resistances in circuit with motors in series. This later became widely known as 'Inch' (as in 'inch forward') and it allowed a speed of about 5mph.
2. Full Series – motors connected in series but all resistances switched out, giving a speed of about 20mph
3. Full On – motors connected in parallel with all resistances switched out, allowing the train to accelerate up to full speed. This was later referred to as 'Parallel'.

The controller had these three positions for the forward direction and two for reverse, preventing any more than series speed in that direction. It had a small handle operating in the vertical plane, rather like an old-fashioned lift controller, which would swing back to the 'off' position when released by the driver so that the motors would switch off. There is no description of a deadman feature being provided in the original installation to apply the train brakes.

Instead of the line fed system used by BTH, the BW control circuits were powered by a 14 V battery (The Electrician, 1903, p7.). The battery was charged from the 600 V supply and a manually variable resistor was connected in series with it to allow the charge rate to be varied. There was also a relay to prevent the battery discharging through the resistor.

The BW system first appeared on the London Underground in 1903 on one of two prototype District electric multiple unit trains which became known as the A Stock (Bruce, 1983, p.30). The other train had BTH equipment. These two 7-car trains were ordered for the Ealing & South Harrow line where, following the arbitrator's decision in favour of the DC electrification scheme, the UERL had installed their trial 4-rail 600 V DC system.

The Metropolitan got a second version (Dawson, 1909 p. 333, Benest, 1964, p. 55). In this design, the drum controller was rejected, for reasons similar to Sprague's original setup, being insufficiently robust for the power of the motors, and it was replaced by a device known as a 'turret controller'. Like the BTH equipment, this had contactors, introduced because they were more robust than the simple finger contacts of the drum controller. However, unlike the electro-magnetic BTH system, each BW contactor was operated by a compressed air piston controlled by a small electrically operated valve. In the BW turret version, they were arranged in a circle around an air supply pipe and housed in a circular steel bin. Apparently, a single, 18,000-amp blow-out coil was provided for all contactors (Benest, 1964, p. 55).

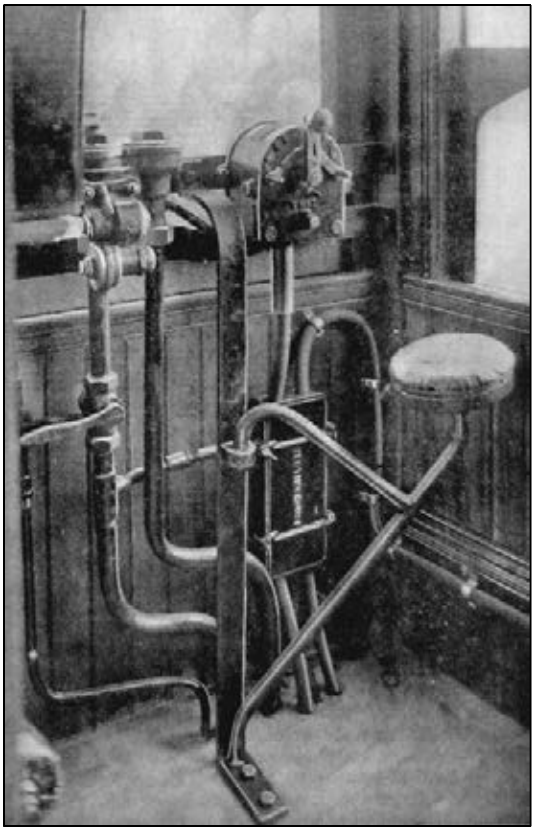


Figure 23: The interior of a District Railway A Stock end motor car cab showing the controls supplied by Westinghouse. On the left is the driver's brake valve and on the right the master controller. The layout of these controls is the opposite way round to the BTH equipped train and it was eventually adopted as standard on the Underground. The Westinghouse master controller seen here operated in the vertical plane as opposed to the horizontal movement normally used. It was inherited from the lift controller design that Sprague devised. Westinghouse later adopted the horizontal setup. The driver's seat might be described as primitive today but similar designs were still in use when the author started his time on the trains in 1964. Photo: Author's collection.

There was an overload switch or 'line breaker', as it would be called today, in the power circuit. If the current in this circuit became too high, it would open and switch off the connections to the motors. It had to be reset manually. It could also be opened manually from a switch in the cab so that the control equipment could be tested without traction power. The control circuit was also equipped with a contact that prevented train power being switched on when the brakes were applied. This was a new idea that was adopted later by the Underground group and which became known as the control governor.

The Metropolitan's BW master controllers were similar to the Mersey railway version but moved in the horizontal plane like BTH controllers. The controller handle was removable and carried with it a plug attached to it by a chain, the plug acting as the control switch. When the driver arrived in the cab, he placed the handle on the master controller spindle and inserted the plug into a socket to connect the controller to the battery supply.

For its electrification programme, the Metropolitan ordered three batches of multiple unit electric stock, dated 1904, 1905 and 1906, corresponding broadly to the year of their delivery. BW turret controllers were fitted to the first two batches and they were also provided on 10 electric locomotives purchased by the Metropolitan in 1904 (Bruce, 1983 pp. 37-39). The multiple unit trains were originally designed to be in 6-car sets, each with two driving motor cars and four trailers. Each motor car had four traction motors controlled through two complete sets of turret equipment mounted under the car. Since it was full-sized surface stock, there was enough room. The two motors on each bogie were controlled by their own turret controller. With this arrangement, the cars were effectively double-equipped.

6.8 BW Difficulties

With the retention of automatic acceleration and quite sophisticated (for the day) attachments like limit switches, the British Westinghouse (BW) equipment was quite bold technically compared with the BTH system but it paid the price in reliability. It very quickly ran into all sorts of technical problems, particularly with the turret controllers. What exactly was wrong with them has not emerged from the author's research but it is likely that the single blow-out coil would have been under extreme stress, having to operate frequently and it must have been subject to a rapidly rising coil temperature. Whatever the trouble was, it was so bad that, in 1906, BW replaced the turret controllers with racks of contactors, similar to the BTH arrangement, providing each contactor with its own blow-out coil. Each contactor had electro-pneumatic operation.

The battery charging arrangement was also unsatisfactory. Although there were two batteries, (The Electrician, 1903) which were separated by a changeover switch. The switch was intended to be operated once a day in the depot to alternate the battery usage. It is not known if this was done on the Metropolitan but, if it was it did not work and, by 1906, a small, 15-volt motor generator (MG), powered off the 600 V DC supply, was added to improve the charging system. Even this was not enough and a second MG was soon added as a back-up (Benest, 1964, p.123).

With these problems, plus rectification work on the traction motors and expensive equipment alterations that were required to the power generating station at Neasden, Westinghouse lost a lot of money on the Metropolitan contract and, largely as a result of this, the company went into receivership in 1907. It survived only with cash injections from British investors and, in 1917, entered into a collaboration with the armaments manufacturer, Vickers. The group chose to call itself Metropolitan-Vickers, a famous name in 20th century electric manufacturing. This part of the company's history is covered in more detail by C. A. Niblett (1980).

Back in 1906, the Metropolitan had, for the moment anyway, learned its lesson on BW technology and decided to equip its third batch of cars, and a second set of electric locomotives, with BTH Type M equipment. The Hammersmith & City Line also got BTH equipment (Benest, 1964, p.147). As with the BW equipment, the Metropolitan used a double-equipment configuration on each motor car, with four motored axles instead of the two used on the tube lines and District. The Metropolitan went back to BW for additional equipment in 1913 and, in the 1920s, they bought more equipment from its successor, Metropolitan-Vickers (Metropolitan Railway 1933, pp. 71-73, 76-77).

6.9 The District

Having tried BW and BTH equipment on its two experimental A Stock trains, the District decided on BTH as its supplier for its main line electrification (UERL, 1903, p.133). They must have realised that the BW system was not up to the job and they were very quickly proved right by the debacle on the Metropolitan. Initially they adopted the same 7-car train formation for the bulk order of 1905 for 60 trains as they had for the experimental A Stock, using three motor cars and four trailers in the formation DM – T – T – MM – T – T – DM. The new order eventually became known as the B Stock. The motor cars had one set of BTH equipment with the two motors on the leading bogie. The MM (Middle Motor car) had driving controls at both ends to allow the train to be uncoupled in service to dispose of the T – T – DM cars during off-peak periods. Because of the lack of driving controls at the trailer end, this arrangement did not last long and 4, 6 or 8-car formations using an equal number of motors and trailers became the standard. Some middle motor cars were also used as single car trains on the South Acton to South Harrow and Hounslow local trips. Control trailers (see box above) were later provided for a time up to the Second World War to allow these short trains to be extended to a 2-car formation (District Railway, 1909).

Control Trailers

In the original arrangements for multiple unit trains, driving cabs were provided only on motor cars. However, it was quickly discovered that running full length trains all day was wasteful so the new tube lines opened in 1906-7 adopted a short train policy for off-peak periods. A 6-car train comprised two half trains in the formation Motor car – Trailer – Control Trailer (M-T-CT) which was coupled to another set facing the other way round (CT-T-M). The control trailer was a trailer car with a driving cab at one end, with its driving controls connected to the motor car at the other end of the 3-car set. When driving from that end, the train was pushed from the motor car at the rear. For peak hour operation, two 3-car sets were coupled to give a 6-car M-T-CT+CT-T-M formation. Some variations had control trailers with cabs at both ends and the Metropolitan (always different) described control trailers as "Driving Trailers".

From this time on, the District used BTH Type M equipment on all its trains until it obtained the version with automatic acceleration in 1927. Its only excursion into double-equipped cars was the F Stock of 1920 (Figure 24). This stock originally had a 3 motor car – 5 trailer formation (including control trailers) with double equipment on each motor car. This gave the stock a 35% increase in power/weight ratio over the older stock, with a consequent increase in current consumption. It was intended that all older trains would be upgraded to match so that an 8-car set would have 3 trailers and 5 motor cars. However, the current supply system would have required a substantial upgrade and the expense of this and of buying more traction equipment for the additional motor cars led to the idea being abandoned. It left the new stock as an over-performer, constantly catching up the older trains in service and causing serious drops in line voltage at peak times. Within a couple of years work began on a scheme to overcome this by removing a set of equipment and motors from one motor car in each train, the affected vehicles then becoming 'single-equipped' (London Transport, 1963).

The District introduced automatic acceleration on its 1927 order for 101 new cars of K Stock. The order was part of a watered down upgrade of its ageing fleet and it involved converting a large number of old 1905-built motor cars to trailers that would match the new motor cars. This fleet was known as 'Main Line Stock'. The remaining oldest cars were left to operate shuttle services on branches and were known as 'Local Stock'. This policy resulted in three batches of cars operating on the line that were largely incompatible: the 1920 Stock, Main Line Stock and Local Stock (Bruce, 1983, p.85).

6.10 The BTH Monopoly

Figure 24: This is an early photo of the District's 1920 Stock, which later became known as the F Stock, under London Transport's management. A hundred cars of this stock were bought as part of an intended upgrade for the District. Motor cars were originally 'double-equipped', i.e. they had two sets of traction equipment. The trains turned out to be too powerful for the traction supply and had to be modified to reduce their current consumption. This train is made up of a motor car (leading), trailer and control trailer. The stock's design allowed for a full train of eight cars, made up of a 3-car unit coupled to a 5-car unit. Collection B.R. Hardy.

By 1907, the main electrification of the District and Metropolitan lines was complete and five electric tube lines had been completed in London, including the Bakerloo, Hampstead and Piccadilly lines in 1906-7. These three later became unified under the name London Electric Railway (LER). The C&SLR and the W&C did not have m-u control but, looking at the totals of equipment purchases of the various lines, BTH were clear winners. They had supplied 617 sets of equipment as opposed to the 135 sets supplied to the Metropolitan by BW. This virtual monopoly went on during the following 15 years when new stock for the Bakerloo, Central and District was all equipped by BTH. They also supplied the District with the equipment for the F Stock and it seemed as if they had an unbreakable position. It was at this point that an abrupt change occurred.

The F Stock was delivered in 1921-22, at the same time that the Underground was about to order the electrical equipment for new tube stock - the Standard Stock, as it became known. BTH assumed they would get the new order. Why would they not? They had been supplying the Underground for the last 20 years and their equipment had proved reliable but, they were in for a surprise. William A. Agnew, appointed as the Chief Mechanical Engineer of the District back in 1907 (I. Loco. E., 1958), was a Scot with a firm reputation and he had an ambitious new assistant, one W.S. Graff-Baker. Graff-Baker was disenchanted with what was perceived as BTH arrogance and, in particular, with their prices for the F Stock, which he thought were outrageous (Birkbeck, 1980). He and Agnew persuaded other electrical equipment suppliers to offer the same control equipment and traction motors as BTH but at a better price. The suppliers quickly rose to the challenge and the first batch of Standard Stock (The 1923 Stock) had equipment supplied by BTH's main rival, Metropolitan-Vickers (MV). Of course, MV were British Westinghouse in new clothes and, such was their keenness to replace BTH as the Underground's main supplier that they even offered to abandon their usual electro-pneumatic system and to provide electro-magnetic equipment to comply with the Underground's specification.

Figure 25: A 4-car train of Standard Tube Stock at Epping about 1957. The four cars are each from different orders ranging from 1923 to 1926. It was during this period that the Underground tried alternative suppliers for traction equipment in place of BTH, who were thought to have become too expensive. The poor reliability of both GEC and Met. Vickers equipment drove the Underground back to BTH for their 1927 order. Collection B.R. Hardy.

Another new supplier, GEC, equipped two of the 1923 batch of motor cars. GEC (the General Electric Company) was a British company, (nothing to do with GE in America), which was founded in 1886 and which supplied lamps and switches. By the end of the First World War, they were well established in Britain but they were new to railway traction. They had an association with Oerlikon of Switzerland, which had been developed back in the closing years of the 19th century in connection with 3-phase motors, but it took another 20 years before they produced multiple unit DC traction equipment to Oerlikon designs in Britain. It seems likely that the installation on the two Standard Stock cars in 1923 was the first in Britain under the GEC name, although similar equipment was supplied for the London & North Western Railway (LNWR) Watford electric m-u stock under the Oerlikon name.

LU drawings (LPTB, 1935) show that both MV and GEC supplied equipment for the 1924 Standard Stock but this was MV's last order for the Underground group. GEC supplied the 1925, 1926 and part of the 1927 batches but BTH were called back into the field for the rest of the 1927 Stock and supplied all future stocks (Figure 25). BTH were brought back because the GEC and MV equipment was not as reliable as expected and the 'Schedules of Special Works'[6] from the overhaul works at Acton that the author inspected, show many modifications were carried out through the 1930s to both types to try to get them to match the reliability of BTH. In future years, both MV and GEC supplied the Metropolitan Railway but neither gained the level of acceptance to make them the preferred supplier.

6.11 Smaller Equipment

In the mid-1930s, improvements to rolling stock design and efficiency came to the forefront. W.S. Graff-Baker, who was in charge of rolling stock design for the Underground in 1933, had joined the District Railway in 1909, shortly after its electrification. He had seen all the problems of wooden body design, he had seen the need for more doors and problems of adding doorways to steel cars and he was well aware of developments in electric traction in the US. He had a number of design initiatives under way when the LPTB took over the organisation in 1933 and he continued with these for the new regime (Graff-Baker, 1938).

One of Graff-Baker's most significant achievements came in 1936 with a prototype tube car design where all the equipment was small enough to fit under the car floor.

[6]"Schedules of Special Works", a series of instructions issued to workshops on the Underground by the engineering offices at Acton Works from November 1927 to 1946, detailing modifications to or technical trials on rolling stock. Lists of these documents are currently stored by the LT Museum at Acton.

With this development, the switch compartment over the motor bogie was no longer required and the much needed space was released for passengers. Motor cars now had (almost) level floors throughout and could accommodate almost the same number of passengers as trailer cars. The breakthrough gave a 15% increase in capacity on a 7-car train. The two principal improvements which allowed this to happen were the introduction of smaller traction equipment and smaller compressors (Bruce, 1983, pp.73-82).

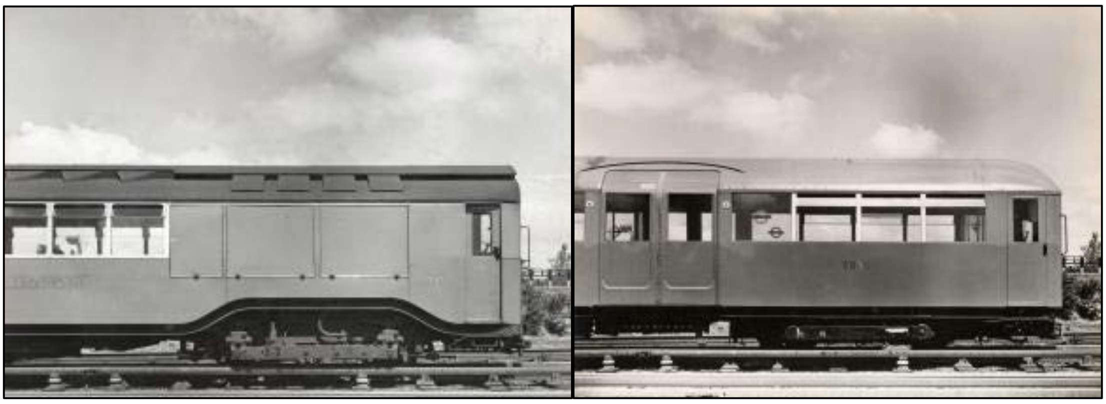


Figure 26: Side views of old and new tube car designs. On the left, the switch compartment end of a 1931 Stock motor car with the raised floor over the motor bogie. On the right, a 1938 motor car showing how the switch compartment area has been removed in favour of passenger accommodation by introducing small motors and traction control system. Photos: LT Museum.

However, squeezing all the kit under the floor was not easy and it required a number of changes to the underframe and floor design. To begin with, the floor was not flat, hence the author's 'almost' remark above. It was lifted slightly over the bogies to give enough clearance for the motors and sloped slightly down at the sides to the doorway areas to maximise door height clearance. All cars were built to the same pattern, even those without motors. The feature survived until smaller traction motors allowed a completely flat floor on the 1967 Tube Stock. The author noted in an inspection of the vehicles that the sloping floor has been revived on the 2009 Tube Stock for the Victoria Line, which needs more room for bogie clearance.

The prototype 1936 car underframe structure was a completely new design. Previous designs had cantilevered transverse stiffeners across the underframe in the area between the bogies. These were provided to strengthen the structure but they restricted the space available below the floor for equipment. For the new cars, the transverse cantilevers were eliminated and deeper solebars and longitudes were provided. The traction equipment and other bits and pieces which had been in the switch compartment were tucked into the spaces between the solebars and longitudes. The seat risers protecting the wheel areas were strengthened to reinforce the longitudes so that they became part of the underframe structure (Figure 27). New, heavy body bolsters were added to absorb the traction forces arising from having the motors tucked under the passenger areas.

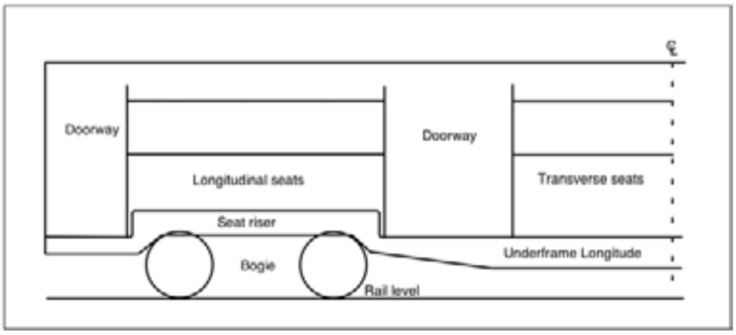


Figure 27: Schematic of post-1935 tube car design showing the seat riser as part of the structure of the car and the deep underframe longitude provided. This arrangement survived on new trains until the 1990s. Drawing: Author.

The new cars formed the prototypes for the next generation of tube stock and were put into production as the 1938 Tube Stock. The same basic door/seat layout (with minor variations) has remained for all subsequent tube car builds and will survive well into the 21st Century. The author was familiar with all these types of vehicles as both operator and engineer.

6.12 Traction Equipment Shrinkage

The major development in equipment design for the new tube stock was in getting the traction motors and control equipment to fit under the car floor. This was done in two ways. First, the motors were made smaller but the number was increased to give the same level of power and they had to be distributed over more cars in the train. For a 7-car Standard Stock train, three motor cars housed six 240 h.p motors but, on the 1938 Tube Stock, there were ten 168 h.p motors spread under 5 cars, actually giving a higher powered train (see Table 3 below).

The second size reduction was achieved by getting the traction control equipment to fit under the floor. The smaller powered motors allowed a slight reduction in resistor grid size for each pair of motors but the real reduction was in the contactors used to switch the resistors out during acceleration. They were redesigned and repackaged and they became part of the system known as the PCM – Pneumatic Camshaft Mechanism.

The novel feature of the PCM system was the reduction in the number of contactors required to carry the full traction current if they opened. Up to this time, each contactor in the traction motor power circuit could open under load at any time during the acceleration sequence, causing an arc. If this was not suppressed, it would quickly burn off the ends of the contact tips, so each contactor had a large ‘blow out’ coil and an ‘arc chute’. The coil was designed to extinguish the arc, or blow it out through the arc chute as the contact tips separated (Agnew, 1937, pp.119-120). It made a loud ‘plop’ if it blew out. Naturally, each contactor required a lot of space and, with fourteen of these in a motor circuit, a large section of the switch compartment was filled with them. Passengers travelling in motor cars could hear the rhythmic clack, clack, clack of the contactors as the train accelerated away from stations.

On the PCM equipment, the control sequence was completely redesigned so that there were only two ‘load bearing’ contactors. These became known as Line Breakers (LBs). They were used as the only switches which separated the equipment from the ‘line’ - the traction current supply - under load. Any time there was a break in the current supply or the contactor operating sequence, it was detected by the control circuit and this opened a contact which caused the Line Breakers to open (Agnew, 1938, p.16).

The contactors were made smaller and were grouped together on a camshaft. The camshaft was driven by compressed air against an oil reservoir. As the camshaft rotated, the contactors opened and closed in sequence to cut out the resistors during the acceleration process. Again, this process can be heard as the older type of train (pre-1992) accelerates.

It is worth noting the move to pneumatic operation of traction equipment. Up to this time, the tube lines and District had relied on the tried and tested electro-magnetic BTH control equipment. BTH’s move to pneumatic operation and the Underground’s acceptance of it was something of a leap of faith, even though they had tested the system on some of the 1936 experimental cars. Their faith was justified, as the system proved capable, once it had settled down.

Table 3 (at the end of this Chapter) shows the train weights, traction motors types, h.p and power/weight ratios for a selection of the main types of Underground train. It is actually very difficult to get accurate figures for power/weight ratios, since published figures do not always agree, they do not always make clear the difference between 1 hour and continuous ratings for motors and measurement criteria vary. Gear ratios and motor designs affect performance, with some motors being designed for high acceleration and low top speed while others are designed for a more gentle acceleration and a high top speed for longer distance running. Car weights vary with modifications applied during their life and even London Underground’s own power figures are sometimes calculated on 630 V or 575 V, depending on whether the engineer used the nominal or the standard average voltage. However, using published sources, checking figures and converting metric back to imperial measurements for consistency, the author offers a representative list of Underground train power, past and present in Table 1 below.

6.13 KLL4s

Another big consumer of train equipment space is the compressor and its main air reservoir. These were originally mounted in the switch compartment of pre-1936 trains but, for the new design, they were simply reduced in size and increased in number and spread along the trains so that there was actually an improvement in capacity. It also became normal from this time to provide separate reservoirs for doors and traction equipment on individual cars.

The author’s experience of pre-1938 train compressors was that they were large, heavy and noisy. They consisted of a 630 V DC motor and a two-cylinder pump. To get an air pump with the capacity required for intensive railway service under the floor of a tube car was another difficult design task. It was achieved by using a completely new design, originally developed for trolleybuses. The new compressor was a high speed, rotary vane type built by Bernard Holland to a Swiss design, known as the KLL4 (Bruce, 1983, p.76). It was much quieter and smaller than the older ones but it was specified to have the same capacity and performance as the reciprocating compressors. Because most of the space under the motor cars was occupied by traction equipment, the compressors were mounted under the trailers. Their 630 V DC power supply was fed from the adjacent driving motor car. Placing compressors under trailer cars became a standard feature of Underground train design for many years.

In service, the actual performance of the KLL4s left much to be desired. In spite of the specification, they were too small, which as the author knew well as a motorman, made recharging the air system on the train very slow. Also, they were not robust enough for the hammering they got on the Underground and they were difficult to maintain. Many were later replaced by more robust, small, reciprocating designs developed after the war (Bingham & Bruce, 1965, p. 504). Unfortunately, in the experience of the author, they were noisier than the rotary type, but they were more reliable.

6.14 Four-Rail Traction

As we have seen, London Underground has an almost unique traction power supply system. Traction current is supplied to trains at a nominal voltage of 630V DC via a positive conductor rail mounted on the outside of the running rails and a negative rail mounted in the ‘4-foot’ between the running rails. The dimensions of the current rails are shown in Figure 28. This arrangement is described as a ‘4-rail’ system, so as to distinguish it from a more common '3-rail' system, where the 3rd rail carries the full line voltage and the return is carried by one or both running rails at or near earth potential.

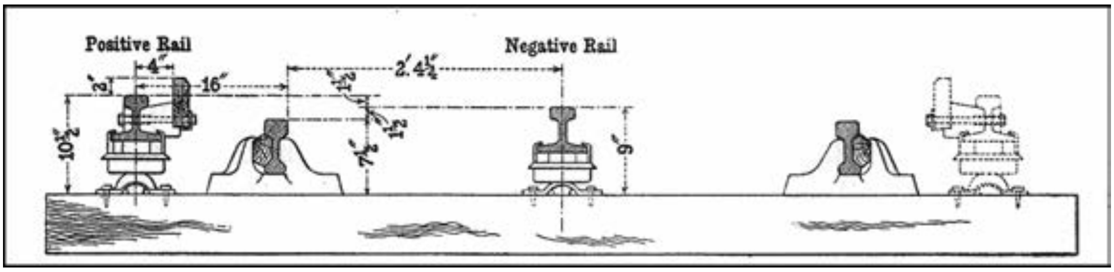


Figure 28: Cross section of District Railway track used for its main line electrification in 1905-6, showing the dimensions of the positive and negative conductor rails in relation to the running rails. The voltage was originally set at 600 V DC, arranged with the positive rail at +400 V and the negative rail at -200 V. The voltage was raised to 630 in the 1930s and is currently gradually being raised to 750. This 4-rail arrangement was adopted by the Metropolitan and the tube railways built by the UERL. It remains to this day. Drawing: Dawson (1909, p. 492).

It should be noted form the diagram that the height of the top of the positive rail is 3 inches above the running rail, while that of the negative rail is 1½ inches or 50% of that of the positive rail (Figure 28). This proportional difference is reflected in the voltages of the two rails in relation to earth. The current rails are bonded to earth through resistances (Bletcher, 1987, p. 321) so that the positive rail is nominally at +420 V while the negative rail is at -210 V.

The only other railway known to the author that is currently using a 4-rail supply system is Line 1 of the Milan Metro, where the voltage is 750 DC. Some other railways in Britain did use the 4-rail system but these were converted to 3-rail operation in the mid-20th century. The former London & North Western Railway suburban routes based on Euston the so-called 'New Lines', used the 4-rail system because they shared track with the Underground's District and Bakerloo Lines. The 'New Lines' were converted to 3-rail operation in the 1970s (although 4-rails are retained as far as Harrow & Wealdstone for Bakerloo operation) and now form part of the London Overground system. On the other hand, the London & South Western Railway scheme for electrification out of Waterloo, started in 1915 (Cock, 1947, p. 117), used 3-rail traction, even though the company's lines to Wimbledon and Richmond had already been electrified on the 4-rail system ten years earlier in order to provide the District Railway with running powers for their new electric trains.

6.15 Reasons for the Adoption of the 4-Rail System

The development of electric traction in the late years of the 19th century was driven by the expansion of urban tramways using DC voltage overhead lines as the means of supply. As development moved towards heavier rail systems, both urban and main line, the transmission of DC current at low voltages (in the range of 500 to 800 V) via an overhead line, required too large a dimension of conductor to provide the energy required, so a third rail, laid at ground level, was adopted as the conductor (Dawson, 1909 p. 479).

Figure 29: Photo of part of London Underground track (Jubilee Line) showing conductor rails with a gap as provided at a substation. Photo: Richard Griffin.

Return current was, in both cases via the running rails. In the case of the Central London Railway (now the Central Line of the London Underground), which opened in July 1900, both running rails were cross-bonded at 60 ft. intervals and the rails were bonded to the cast iron tunnel lining at the substations (Parshall et al. 1903). This was an attempt to reduce the risk of stray currents electro-magnetically affecting other services such as telegraph and telephone systems or causing corrosion of water and gas pipes. It was already a well-known phenomenon, having been experienced on the first electric tramway built in the United States in 1888, as related in Chapter 2.

The choice of the 4-rail system was determined with the particular circumstances of the District Railway in mind. Arthur R. Cooper, Chief Engineer of the Underground Electric Railways of London Ltd (UERL) in a paper delivered to the Institution of Electrical Engineers in 1927 wrote, "*Undoubtedly the chief feature determining the decision to adopt an insulated return was the possible injurious effect on apparatus of other concerns such as gas pipes, water pipes, telegraph or telephone cables and, in particular, the Government Observatories*" (Cooper, 1927, p. 390). It was considered that the tube lines already opened were better suited to 3-rail operation because of their containment inside a cast iron tube, which acted to contain the return currents along the line of route. This was not the case on the District, where the lines were built to the 'cut and cover' system and were much closer to the surface, with its network of pipes and cable runs and therefore much more likely to cause trouble

(Cooper, 1927). The 4-rail system was expected to resolve the issues.

Another important factor Cooper (1927, p. 390) mentioned was the intention to adopt a system of automatic signalling, using DC track circuits as a means of train detection. This proposal would have rendered the use of the running rails for the traction return circuit impossible. In the author's view, this was more important than the risk of electrical interference or corrosion, which could have been controlled by suitable protection measures.

Another point made by Cooper was that the 4-rail system "*allowed the railways to continue working if one pole became earthed due to a failure of insulation*" (p. 390). He noted that cases had occurred where "for many hours the system…operated with the positive conductor earthed". This had its risks, as described below, but it was allowed to go on and still is today, under controlled conditions.

The other tube lines that were taken into the Underground fold (the Central London the Great Northern & City and the City & South London) all had their 3-rail systems converted to 4-rail. The last line to be converted was the Central London, the work being carried out in 1940 in preparation for extensions into the London suburbs and the adoption of 'Standard' (4-rail) tube rolling stock.

6.16 Retention of the 4-Rail System

The 4-rail system used by London Underground has, over many years, been widely discussed in terms of its efficacy in relation to more traditional 3-rail systems. The most obvious questions relate to:

- The cost of maintaining an additional rail;
- The cost of providing and maintaining the negative collector shoegear;
- The obstruction caused by the negative rail during emergency evacuation;
- The problems associated with the earthing of one pole or the other at different locations on the system.

Questions are asked on a regular basis as to why the system should not be converted to a more conventional 3-rail system. In the author's own experience, since 1980 there have been two major assessments of the proposal by London Underground and, in both cases, it was recommended that the existing system should be retained. No literature for either of these cases has been found but Cooper (1927, p. 390) provided a useful description of the issues that exercised minds on the same subject in those days. In the end, the real issue relates to the cost of conversion and the lack of evidence for any real benefits. The most significant costs relate to the provision of impedance bonds at the ends of each track circuit. Cooper (1927, p. 390) quoted that the Underground had an average of nine track circuits per mile of track and that the cost of providing impedance bonds for these was almost the same as the cost of providing the additional rail. There is also the relationship of the cost of either a negative earth brush for the 3-rail system or negative shoegear for a 4-rail system. The cost of converting a fleet of over 4000 vehicles from one to the other is not insignificant and, on tube vehicles, there is little space on the bogie for a reliable return circuit brush system. In addition, management of stray current throughout London's sub-surface lines would be extremely onerous.

6.17 Earth Faults

On a 3-rail system, most instances of an accidental earth contact on the positive rail will cause a rapid rise in the current that will be detected by the protection system and will cause the supply circuit breaker to open. This does not happen with a 4-rail system. As Cooper (1927, p.390) explained, an earth connection to earth on one pole of the system would allow the voltage on the other pole to rise to the full voltage of the system and the system would continue to function. However, it often exposes weaknesses in the supply circuit and can lead to a dangerous situation arising if another earth occurs on the opposite pole. Cooper (1927, p. 391) quotes a case where a positive earth took place at Lambeth North on the Bakerloo Line and, within 27 minutes a total of five faults appeared on various parts of the tube system, including a negative fuse box fire on a train at Highgate, some 7 miles away on another line. The reason for these occurrences was the connectivity arrangement of the system.

Originally, the whole of the UERL system was supplied from the company's power station at Lots Road, Chelsea and all the lines on the 600-volt system[7] were linked. With the increasing realisation that an earth fault in one location could often cause fusing and arcing in another, the District supply was separated from that of the three tube lines and later the tube lines separated from each other, sometime prior to 1927. Despite the problems noted by Cooper (1927), little more seems to have been done until after the Second World War. In July 1948, it was announced to staff that the traction system was to be divided into six areas known as Metropolitan, Northern, Southern, Eastern, Western and Central Line (LTE, 1948). The sections did not relate to line separation but rather to the establishment of areas. The 'Eastern' area included the then British Railways line between Campbell Road and Upminster. Some sections were not coupled to the Underground system – the Hammersmith & City Line (west of Edgware Road), the line north of Queen's Park, Putney Bridge – Wimbledon and Gunnersbury – Richmond.

[7] The original voltage adopted by the UERL was 600 but this was uprated to 630 V in the 1930s.

The work on implementing the scheme proceeded slowly. The divisions between sections could be seen on the track by the location of 48ft gaps in the current rails. The purpose of these was to prevent the collector shoes of one car bridging the gap between sections. This did not address the issues with trains on the District and Metropolitan lines that were equipped with buslines but it was intended that these would eventually be replaced with new cars that would not have power buslines. The replacement programme began in 1949 with the introduction of the first of the District Line’s R Stock (Bruce, 1983, pp 98-103).

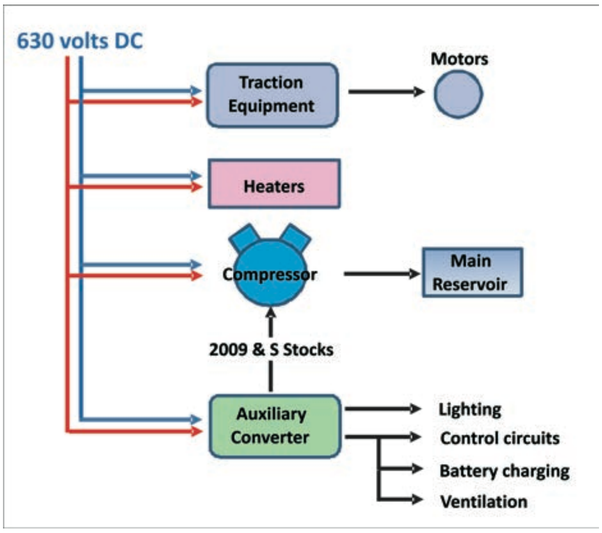
Additional sub-divisions of the traction current system were added over a period of several years and Bletcher (1987, p. 321) described how the Underground’s conductor-rail system was then split into sections, typically about 15 km long, each fed by some five substations. The negative-rail potential was monitored to show earths and the readings transmitted to control rooms. If an earth appeared, the line controller would see if the fault moved from one section to the next so that he could determine if the fault was on a train or on the infrastructure. Bletcher (1987, p. 321) observed that the length of sections had to be a compromise, since shorter lengths would make it easier to pinpoint the location of a fault and thus reduce the risk of both a positive and a negative fault occurring on the same section. On the other hand, a longer section gives better utilisation of rectifying plant and will offer more chance of a receptive load for regenerative braking. At that time, regeneration was being reconsidered as a possibility on the Underground. Regeneration was to turn the whole sectionalisation philosophy on its head.

6.18 Sectionalisation & Regeneration

With the desire to allow more effective regeneration, longer sections have been re-introduced on some lines. On the Victoria line, for example, the original setup from the line’s construction in the mid-1960s, was to sectionalise every substation feed so that there were ten separate sections on the 20km long line. With the introduction of the 2009 Tube Stock, in order to allow better distribution of regenerated current, the number of sections was reduced to three (Chymera, 2012).

This strategy was also applied on the Jubilee line where the number of sections over the 36km line was reduced to three. However, an incident on that line on 19th April 2011 (TfL, 2011), described in an internal report, seen by the author but not now available, demonstrates clearly how train design and power system design can jointly cause severe disruption if they have not been properly co-ordinated. On this day, a negative earth on the traction system was recorded east of Canary Wharf at 18:39. As a result, a large number of trains east of Finchley Road lost traction. This was due to the on-board traction equipment being shut down by the trains' earth fault detectors. A consequence of a lack of traction power is the loss of power to the on-board compressors as all 600 V systems are supplied through the same High-Speed Circuit Breaker (HSCB). Older stocks have separate compressor contactors, so they are independently supplied. On the 1996 Tube Stock, to reset the HSCB requires compressed air. If the traction current is off for a long period, the air supply tends to leak off, preventing resetting of the HSCB and thus preventing starting of the train. In addition, the on-board batteries will also become discharged.

Figure 30: Schematic of the 630-volt supply systems on Underground Rolling stock. The traditional arrangement was to provide individual contactors for each of these systems but modern designs have reduced the isolation to one 'High Speed Circuit Breaker' for all systems. The trend now is for compressors to be powered from the auxiliary converter rather than directly from the traction supply. There is now a programme to gradually upgrade all lines from the existing 630 DC voltage to a 750-volt traction supply. Drawing: Author.



In this incident, some trains could not be restarted. Teams were sent out to 'pump up' stalled trains using a variety of pumps, including emergency compressors and foot pumps. At one location, one of these failed and another one had to be sent for. The service on the line was suspended east of Neasden for the rest of the evening. The last train was finally stabled at 03:45 the next morning. The cause was eventually found to be a traction equipment case cover that fell off a train and jammed under the negative rail near West Ham.

The reduction of sectionalisation gaps on the line meant that earth faults could spread along the long sections. In this incident, it was the reason why the earth fault was registered by so many trains at once. One lesson learned from this incident is that 2009 Tube and S Stocks both have electro-magnetic HSCBs so they do not need compressed air to restart the compressors. In a discussion with the author, one LU senior person took the view that the rarity of earth faults on the infrastructure meant that the risk was low, particularly when put against the energy savings achieved from regeneration and that this made the long traction current sections a viable solution.

6.19 GTO for AC Motors

Although 3-phase AC motors with power electronics had been tried by Brush Traction at Loughborough on a locomotive as early as 1963 (Duffy, 2003, p. 340), it was not until the late 1980s that this sort of technology was considered by the railway industry as reliable enough for regular service conditions. LU, fully aware of the pitfalls of new and untried electronic technology, conducted a series of trials of power electronics in the 1970s (Dobell & Fried, 1991, p.56) but only proceeded to adopt them for the 1992 Tube Stock[8]. Even then, there were fears about interference with signalling systems, the complexity of the control systems, the space required for all the equipment and its long-term reliability, not to mention its cost. So, AC motors were not deemed suitable when the ’92 Stock was ordered, hence its DC motors with GTO Chopper control. The step-by-step approach was the result of an awareness by the Underground’s engineers of the specific details of the system they worked on.

3-phase AC motors became the ultimate prize for traction engineers. The two big advantages of the 3-phase design are that one, unlike a DC motor, the AC motor has no brushes since there is no need to physically connect the armature and the fields and two, the armature can be made of steel laminations, instead of the large number of windings required in DC motors. Also, it is smaller and lighter than a DC motor of similar power, making bogie design potentially better. These features give it a better power/weight ratio, make it more robust and cheaper to build and maintain than a DC motor. Once a suitable 3-phase control system had been proven and the technical problems with interference for signalling and external electrical systems were overcome, AC motors became the propulsion of choice for new stock. On LU, the first stock to get them was the 1996 Tube Stock.

The AC system applied to the ‘96 Stock uses GTO choppers and it incorporates Variable Voltage Variable Frequency (VVVF) control (Neil, 2016). The system involves complex control and switching techniques which require the GTOs to switch on and off at exactly the right moments and to do it at high frequency (around 300 to 900 times a second) so the right amount of current is available at the motors when needed. The control of the voltage pulses and frequency has to be adjusted with differing motor speeds. The changes which occur during this process produce a set of characteristic buzzing noises which sound like the ‘gear changing’ of a road vehicle and which can clearly be heard on the ’96 Stock as it accelerates and brakes.

[8] There was, apparently, no attempt to introduce synchronous motors. The author can find no references to it in the LU related literature so it might be assumed that the Underground’s engineers were aware of its limitations in the railway traction environment and preferred to wait until asynchronous control systems were sufficiently developed for railway use.

6.20 IGBTs

Having got AC drive with GTO choppers almost universally accepted in the mid 1990s as the traction system to have, power electronics engineers then perfected the IGBT or Insulated Gate Bipolar Transistor. The transistor was the forerunner of modern electronics and it can be turned on or off like a thyristor but it does not need the high currents of the GTO thyristor turn-off system. In its early development, the IGBT was only capable of handling fairly small currents and it first appeared on LU stock in the 1996 Tube Stock auxiliary converter (Neil, 2016) but it was quickly developed so that the latest devices can handle thousands of amps. Now it is standard in traction applications and was it provided for the 1995 Tube Stock[9]. It is also now used on the 2009 and S Stocks. Its principal benefit is that it can switch a lot faster (three to four times faster) than GTOs. This reduces the current required and therefore the heat generated, giving smaller and lighter units. The faster switching also reduces the cruder ‘gearing’ of GTOs and makes for a much smoother and more even sounding acceleration buzz from under the train. With IGBTs, ‘gear changing’ has gone.

In all the instances where 3-phase traction was introduced, it was necessary to ensure there was no risk to the integrity of signalling circuits caused by interference from the power systems. The solution was to ensure audio frequency track circuits of the correct design were installed and the author recalls that on some Underground lines, extensive track circuit replacement was necessary in order to allow 3-phase trains to run.

6.21 Modern Control

With the development of systems such as doors, E.P. brakes, communications and a multitude of other control and fault indications being transmitted along trains, jumpers connecting systems between cars multiplied over the years and the number of cores increased in some of them from ten to more than forty.

Once electronics appeared, ways of reducing the number of train wires offered themselves. Most promising was ‘time division multiplexing’, where one wire can be used to transmit different sets of data or information. The data is sent in packets which share travel time on the wire. The author first saw it used on the 1973 Tube Stock for its infamous Fault Annunciator (of which more below). Being electronic, this sort of system was (and still is) regarded as basically unstable, so hard wiring is retained for most safety circuits.

[9] Although described as 1995 Tube Stock, the fleet was built and delivered after the 1996 Tube Stock. It thus had more modern equipment.

In the case of the 1990s Tube Stocks, the traction/braking control uses pulse width modulation (PWM) on a wire passing to each set of traction equipment on the train. PWM is a variable electronic signal, which has similar characteristics to the electronic traction inverter controller. The PWM signal is altered to vary the voltage and frequency of the traction inverter and the inverter allows the power supply for the motor to match the demand for power or braking.

The arrangement is shown schematically in Figure 31. The PWM signal is sent by an encoder, which responds to the demand from the driver's controller or the ATO system on a train if it has one. The encoder sends the PWM signal along the train to each car with traction equipment. Here, the demand signal is used to tell the inverter controls (the PWM Controller) what level of power to pass to the motors. The performance of the motors is then fed back to the inverter controls to verify that the traction effort achieved is equal to that of the effort demanded - the classic feedback loop.

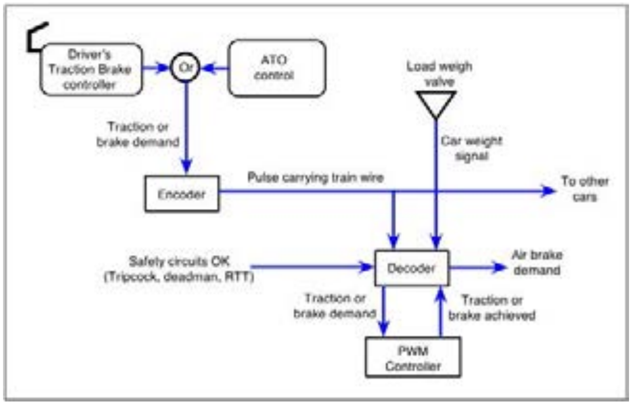


Figure 31: Simplified schematic of Pulse Width Modulation (PWM) control showing how the demand for traction or brake is requested electronically and how the air brake is added if insufficient dynamic brake is available for the brake rate demanded. Drawing: Author.

In the author's experience, drivers took some time to get used to the new system. As described above (Section 6.7), traditional traction control has three power positions for the driver, 'Inch/Shunt', 'Series' and 'Parallel', the resulting speeds being loosely governed by the electrical properties of DC traction-motors. Modern traction control however involves a notchless 'motoring arc' between 'Off' and 'Full motors', with the selected position on the arc usually regulating the amount of power delivered to the AC motors (Bombardier, 2009).

In case of an electronic defect, there is a default 'power on' hard wire, which used to be referred to as the 'actuating' wire on traditional controls. This provides a default acceleration rate of 77% to 100% (depending on the stock) as long as the controller is in an 'On' position. The trains also have a split traction control system so that two sets of control wires are used – one controlling the 'A' cars and one the 'D' cars. If one set fails, the other will allow half the train's power to be used. This was a significant feature introduced on the 1973 Tube Stock.

The 1973 Stock was also equipped with a 'Fault Annunciator' (with the unfortunate initials FA) that quickly became excoriated as unreliable and unfit for the rigours of railway service. Within a few years, it was replaced with a new system known as a Train Equipment Panel (TEP). This was an early form of electronic train management system. The stock also had significant problems with a new form of camshaft controller, with microswitches, miniature relays, key operated switches and brake components. It underwent three major engineering modification programmes within the author's working life with it. It was over 30 years before it achieved the reliability of its predecessors.

6.22 Braking

Until the 1970s, London Underground almost invariably specified the Westinghouse automatic air brake for its electric trains. Only the Metropolitan Railway retained some units with Vacuum brakes for a while (Metropolitan Railway, 1933, pp. 205), believing that it would switch them from steam to electric traction en route in a versatile service pattern.

Soon after the development of the multiple unit system, systems for electrical control of air brakes appeared in the US (Parodi, 1913), largely in an effort to get a graduated release, something quite difficult to obtain on the air brake systems then available. Eventually, in the late 1920s, the electro-pneumatic (EP) brake arrived in London in a sufficiently developed form for service use and was integrated into the Westinghouse system for all tube stocks built after 1929. Some of the earlier stocks were converted too so that by 1940, all tube lines had all trains with EP brakes. Such was the improvement in stopping accuracy for EP equipped trains that lines previously limited to a 6-car train formation could increase lengths to seven cars.

Earlier in this work, we saw that Frank Sprague knew that the electric motor was basically the same machine as a dynamo and that the motors used for traction on electric trains could be configured so as to provide a braking effort, producing electrical energy as a result. Nowadays, we call it dynamic braking or regeneration. Sprague tried it on his pioneer Chicago South Side Elevated traction equipment and it sometimes worked but it was crude and unreliable. It fell into disuse then but the idea that it was possible never went away.

Figure 32: A 4-car O Stock train of 1937 standing at the 'Boston End' of Northfields depot. This was the first Underground stock to have mercury retarder control of braking. It was also fitted with a new system of traction control known as a 'Metadyne', which provided a facility for regenerating braking current into the power supply. Photo: LT Museum.

It eventually appeared on London Underground in 1935, when a set of six old Metropolitan Railway saloon stock cars were experimentally equipped (LPTB, 1934) with a new traction control system which included a form of electric braking where the motors generated power which could be fed back into the supply for use by other trains. The control system adopted was known as the Metadyne. It was the invention of an Italian named Pestarini and it was marketed in Britain by Metropolitan Vickers (Agnew, 1937, p. 458). It was to be fitted to the new surface stock being ordered at the time, which became known as the O and P Stocks (Figure 32).

Metadyne motor control was derived from the Ward Leonard system, where a motor generator was used to control the motor instead of using starting resistances (Agnew, 1937, pp. 458-470). The idea was that the Metadyne could "change power at a constant voltage to power at a constant current" as it was widely described at the time. The Metadyne was a large rotating machine which was mounted under one of a pair of cars. It was connected to two traction motors on each of the two cars in the unit, so one machine controlled the four motors on a 2-car unit. Three such units made up a 6-car train. The machine was so large that it was necessary to put all the rest of the equipment, such as the compressor and motor generator, under the other motor car of the pair.

Like all new systems, the Metadynes suffered a fair share of problems (Bruce, 1983, p. 94). Number one was the ability of the line to accept regenerated current. If there was nowhere for the current to go, it would not work, so the standard EP system did the braking. Also, the Metadyne machines were heavy, mechanical devices which needed a lot of maintenance and the extra valves and relays for the blending system added to these problems. As they were introduced at the beginning of the Second World War, during the period of the war, they suffered from a shortage of spares and the manpower to fix them. The equipment survived until the mid-1950s, when it was replaced by the then standard PCM resistance control system as fitted to the 1938 Tube Stock and R Stock. The O and P Stock was ‘converted’ and became CO and CP Stock.

All modern trains are fitted with dynamic braking. In London, it started with DC motors in a resistance controlled environment, where the regenerated current was fed back into the resistance grids and dissipated as heat – rheostatic braking. It was still crude and unreliable but it was another attempt to reduce the reliance on friction braking.

The author can attest to the fact that the control is not as refined as EP brake control, so adjustment of the braking rate is not as sensitive and this makes it more difficult for the driver to get an accurate and gentle stop. There is also a tendency, particularly on older trains, to lose dynamic braking from time to time, so the air brake has to be brought in to compensate. Naturally, this is automatic but the response is sometimes not as rapid as the driver would like, particularly because he has to wait for the air pressure in the brake cylinders to build up to the same level of braking as he originally requested. The result can be a tendency for the train to overrun the usual stopping mark. Engineers will say that they have resolved this problem in modern systems but the author has yet to find a driver who would agree with them.

Most Underground trains have trailer cars, so they use only air brakes. They retain the EP brake, which is activated by the driver’s brake demand at the same time as the motor cars’ dynamic braking. In a train with a mix of dynamic and air braking, the control system is designed to give preference to the dynamic brake over the air brake. This calls for a blending system, which automatically selects dynamic brake and then adds air brake as necessary to achieve the required deceleration rate. This can mean that the motor cars will provide almost all the brake necessary and the trailers need very little.

The reduction in the use of the friction brake that has resulted has a significant effect on the consumption of brake shoes. A useful demonstration of this took place when the main line Pendolino type of train had a problem with its dynamic brake control system in 2013 and it had to be isolated while the rolling stock supply company sorted it out. During this time, the author was informed by the depot engineer at Oxley Depot, the replacement period for their brake pads dropped from 18 weeks to 18 days – a 7-fold difference. There is also known to be a significant reduction in energy consumption (up to 17%) and heat (up to 38%) with the introduction of regenerative braking (Tinham, 2007, p. 8).

Having solid state power electronics with IGBTs, allows dynamic braking to be more easily controlled and more reliable. Brake control for the driver of LU's post 1980s stocks is provided in the second segment in his traction/brake controller (T/BC). Between 'off and release' and 'full-service', the driver can select any position to match the rate of braking that he requires. In this respect, the controller is configured in a similar way for both traction and braking. Selection of a position in the traction or braking segment, will select a rate of acceleration or deceleration. Braking control also has a hardwired 'brake on' signal. If the encoder generating the PWM signal fails and has to be isolated, the hardwired signal will automatically provide a 50% service brake when the driver selects brake. In any circumstances, the emergency brake is always available.

6.23 ECEB

The Westinghouse air brake lasted as the Underground's 'fail-safe' braking system for all new stocks until the appearance of the 1973 Tube Stock on the Piccadilly Line. On this stock, for which the author prepared training courses, the train line, used as the control pipe for the Westinghouse brake, was replaced by a 'round the train' (RTT) circuit which became known as 'Electrical Control of Emergency Braking' (ECEB).

The idea is simple. Keep the wire energised and the brakes remain released; de-energise the wire and the brakes go on. An electrically controlled valve on each car responds to the de-energised wire by opening a connection between a brake supply reservoir and the brake cylinders on the vehicle, giving an emergency brake. The dynamic brake is not used for emergencies, it is not fail safe.

In order to ensure that, if the RTT circuit fails, there is a 'get you home' circuit, a second RTT circuit is provided but it only allows movement at slow speed – up to 10mph. This is simply because, if the full speed circuit has gone wrong, some form of safety protection has been lost. Each safety device on the train is connected to the RTT circuits in one way or another and each system has a cut-out switch so that it defaults to the 10 mph circuit. Some circuits, like the passenger alarm, have a circuit for each car with a relay connection in the RTT circuit so that the car can easily be identified and isolated if necessary. Such 10 mph excursions are invariably time consuming and create huge delays.

6.24 Analysis

In this case study, it is shown that for the initial large scale electrification orders of the 1903 to 1907 period, there were two main suppliers and that one proved more reliable than the other. The less reliable system may have been due to the use of a new and untried electro-pneumatic control that was more complex than its rival electro-magnetic system. Perhaps, the Metropolitan Railway's choice of BW related to a financial incentive or to a package that included the power supply system. They also then tried BTH equipment but then went back to BW. The question as to why remains unanswered but it is noteworthy that, after World War I, the price of BTH equipment drove the LER to try MV & GEC. However, the equipment from these suppliers was not reliable, so they went back to BTH – a lesson that should be noted today when price seems to be the main driver for many procurement strategies.

The 1930s saw experiments in miniaturisation and regeneration. The miniaturisation experiment was successful but regeneration was not. The failure to get regeneration to work effectively was largely due to the mechanical complexity of the system and the failure of manufacturer's support. Miniaturisation was successful because of a combination of prototyping and a system understanding of the relationship between body underframe design and traction equipment. It provided significant passenger capacity improvement. Regeneration was not successful until the introduction of solid state power systems for the 1992 Tube Stock and only after extensive upgrades to the power supply system.

The 4-rail power supply unique in London because of an early example of a system design approach. There was a need to reduce corrosion risk, introduce automatic signalling with DC track circuits, to keep running when there was an insulation problem and to widen the space between substations. Later, the problems with earth faults and insulation breakdown led to sectionalisation but this in turn reduced the effectiveness of regeneration. The reversal of the sectionalisation policy to improve the effectiveness of regeneration is now, with modern on-board earth detection equipment, considered acceptable.

6.25 Conclusions

The historical data on the development of electric traction equipment over the period between 1901 and the present day, shows that electric traction system development in London was generally static for long periods and development was limited to minor enhancements, like the move from manual to automatic acceleration and the adoption of interpoles in traction motors but, on two occasions, major advances took place. The first major change was in the mid 1930s, where miniaturisation allowed all the traction and auxiliary equipment to be placed under the car floor and the second change was the adoption of a solid state traction power system for the 1992 Tube Stock and subsequent fleets.

Looking at it in more detail, it can be seen that by the mid 1930s, the electric traction systems used on the Underground had remained, for almost 30 years, a standard type, the BTH electro-magnetic system. Automatic acceleration had been added to new purchases from 1915 but otherwise the equipment was essentially the same as the Central London's first multiple unit equipment in 1901. In analysing this, the author sees two main reasons. One was reliability. Once it had settled down into full service use on the tube lines and the District, the BTH system proved reliable enough for everyday service on a railway which was showing a rapidly increasing level of traffic. Reliability was proving to be an essential ingredient for a successful urban railway system and the Underground's management was well aware of it. They had learned it the hard way during the large increases in traffic seen on the tube lines and the District during the First World War of 1914-18 at a time when manpower shortages were at their height (Jackson & Croome, 1993). After the war, traffic continued to rise and new lines and extensions were planned. Reliability was already the prime goal for the organisation.

The other reason for the continued use of BTH equipment was compatibility. New vehicles had to couple with and operate in trains with existing cars. Trains were required to be flexible, both in length and composition and the District in particular, bought small batches of similar and compatible cars over a number of years before the purchase of the F Stock in 1920. The decision not to upgrade the power supply system to match the performance of the F Stock was to cost the District dear and, by 1930, after a refurbishment programme carried out on the 1905 fleet, they had three operationally incompatible batches of cars. This was to haunt them for the next 50 years and it affected the rolling stock purchasing policy during the whole of that time. On the tube lines, the move from BTH to alternative suppliers in the mid-1920s was not a success. The management, on both sides, seems to have not fully understood what was required and reliability suffered. Within four years, new orders had been directed back to BTH. They were to be the preferred supplier for a further 40 years.

By the mid 1930s, some lessons had been learned. Miniaturisation of the mid-1930s was the clear ambition of the chief rolling stock designer of the Underground, W.S. Graff-Baker. He had developed a small team to search for solutions that would get rid of the 12-foot long switch compartment on every tube stock motor car. He eventually found several varieties of smaller traction equipment derived from tramcar technology and smaller air compressors to match them. He tried out various systems before going for the big orders. This was a valuable lesson that was sometimes neglected in later years.

In this sequence of development, the usefulness of prototyping was shown in a number of cases – regeneration, miniaturisation of equipment, new brake control systems and new body designs. That said, some of the systems required significant modification after the main production fleet was introduced. The Metadyne regeneration system was not to provide the reliability and performance expected of it and it had to be abandoned half way through the life of the O and P stocks to which it was fitted. It was learned that even prototyping didn't always show up the long term issues. Also, the small KLL4 compressors were found to be not ideal for use on the Underground, even though they had been successful on road vehicles. Another lesson learned here was that what may be successful in one environment may not work in another.

Regeneration was a feature that only came reliably with solid state power equipment for rolling stock traction. The development of solid state power systems was considered sufficiently advanced for it to be taken up in London for the 1992 Tube Stock on the Central line and regeneration followed as each line got new stock thereafter. It did however cause problems with the 4-rail power supply by rendering the previously installed section gaps (to aid earth fault finding) a hindrance to regeneration. In the author's view, this issue remains to be fully resolved, since a large number of trains can be stopped by earth fault detection occurring on a 15km section of line. Whilst this may not be an issue from the point of view of electrical safety or fire risk, it will lead to large numbers of trains being stalled in tunnels and thus create risks to passengers' well-being in confined underground conditions.

Line	Train	Stock + Date	Weight	Motors	Power	HP/Ton
CLR	6-cars	Gate 1903	101 tons	GE66	4 x 125hp = 500hp	4.95
LER	6-cars	Gate 1906	120 tons	GE69	4 x 200hp = 800hp	6.66
LER	6-cars	WJS 1920	161 tons	GE212	6 x 240hp = 1440hp	8.94
LER	7-cars	Std. 1931	170 tons	WT54	6 x 240hp = 1440hp	8.47
DR	7-cars	B 1905	173 tons	GE69	6 x 200hp = 1200hp	6.94
DR	8-cars	F 1920	257 tons	GE260	12 x 234hp = 2808hp	10.93
DR	8-cars	F 1925	252 tons	GE260	10 x 234hp = 2340hp	9.29
DR	8-cars	G/K/L 1935	232 tons	WT54B	8 x 240hp = 1920hp	8.27
Met	6-cars	1904	158 tons	GE76/50M	8 x 150hp = 1200hp	7.59
Met	6-cars	1905/6	158 tons	GE69/86M	8 x 200hp = 1600hp	10.13
Met	4-cars	1905/6	99 tons	GE69/86M	4 x 200hp = 800hp	8.08
Met	7-cars	1927/9 (T)	243 tons	MV152	8 x 275hp = 2200hp	9.05
LT	7-cars	1938TS	177 tons	LT100	10 x 168hp = 1680hp	9.49
LT	6-cars	O Stock 1935	210 tons	MV145AZ	12 x 155hp = 1860hp	8.86
LT	7-cars	CP Stock 1960	240 tons	MV145AZ	12 x 155hp = 1860hp	7.75
LT	7-cars	R Stock 1947	200 tons	LT111	14 x 102hp = 1428hp	7.14
LT	7-cars	1959TS	144 tons	LT112	10 x 102hp = 1020hp	7.08
LT	8-cars	1967TS	203 tons	LT115A	16 x 106hp = 1696hp	8.35
LT	7-cars	1972TS	164 tons	LT115B	12 x 106hp = 1272hp	7.76
LT	6-cars	1973TS	155 tons	LT118	16 x 88hp = 1408hp	9.08
LT	8-cars	A60 Stock	215 tons	LT114	16 x 86hp = 1376hp	6.4
LT	6-cars	C69 Stock	155 tons	LT117	12 x 116hp = 1392hp	8.98
LT	6-cars	D78 Stock	144 tons	LT118B	16 x 88hp = 1408hp	9.78
LU	8-cars	1992TS	167 tons	LT130	32 x 63hp = 2016hp	12.07
LU	7-cars	1996TS	177 tons	LT200	16 x 113hp = 1808hp	10.21
LU	6-cars	1995TS	158 tons	G355AZ	16 x 120hp = 1920hp	12.15
LU	8-cars	2009TS	194 tons	BT	24 x 100hp = 2400hp	12.37
LU	8-cars	S Stock	211 tons	BT	32 x 100hp = 3200hp	15.17

Table 3: Power/weight ratios of LU Rolling stock 1903-2012. The data is converted to imperial measurements to allow comparison. Table by Author from various published and unpublished sources listed below.

Hobart H.M. (1910), *Electric Trains*, London & New York, Harper & Brothers, p. 94.

Thomas, J.P. (1928), *Handling London's Underground Traffic*, London's Underground, London, p. 146.

LPTB (1935), *Dwg. No. 21778, General Particulars of Rolling Stock*, LT Museum, Acton.

Thomas, J.P. (1928), *Handling London's Underground Traffic*, London's Underground, London, p. 127.

Benest, K. (1964), The Rolling Stock of the Metropolitan Railway 11, *Underground*, Vol. 3, (No. 4), p. 53.

Metropolitan Railway, (1933), *Rolling Stock Blueprint Book*, LT Museum, Acton.

London Transport (1970), *Rolling Stock Data File*, LT Museum, Acton.

Neil, G. (2012), *Rolling Stock Information Sheets, 4th Ed.* Available at https://www.whatdotheyknow.com/request/398342/response/972415/attach/3/Info%20Sheets%204%20Edition%20R.PDF.pdf?cookie_passthrough=1. Accessed 17 March 2017.

7 Car Doors and Passenger Flows

7.1 Introduction

One of the defining features of an urban railway operation is the volume of passengers that have to be handled by the system, both on trains and at stations. This was not properly understood in the early days of operation in London and, up to the start of World War I in 1914, there was a gradual increase in the traffic on the Underground railways that did not particularly stress the train carrying capacity but there were problems with station dwell times because of long boarding and alighting times. During the war, traffic rose steadily, creating more problems for capacity capability. This chapter examines these problems and their solutions and demonstrates the value of understanding the relationships between car body design, door placement and opening size and the arrangement of seating compared with doorways. It also demonstrates the lessons learned from the interaction between passengers boarding and alighting from trains and door operation.

7.2 C&SLR Cars

One of the defining features of the London Underground is the small size of the tube tunnels and the restrictions this places on car body design. The original C&SLR tunnels were even smaller (at 10 ft. 2 in) than the ones seen today and the original passenger cars were designed to squeeze into this very confined space and to negotiate tight radius curves. Each car body was 26 ft. (7.9 m) long and was carried on a pair of bogies with relatively small 2 ft. (600 mm) diameter wheels (Greathead, 1896). A normal size of railway carriage wheel in those days was about 3 ft. 6 ins (1150 mm). The trouble was that the C&SLR wheels had to fit under the car floor and still leave enough clearance inside the car for people to be able to stand. It was a tight fit and it was solved as shown in Figure 33.

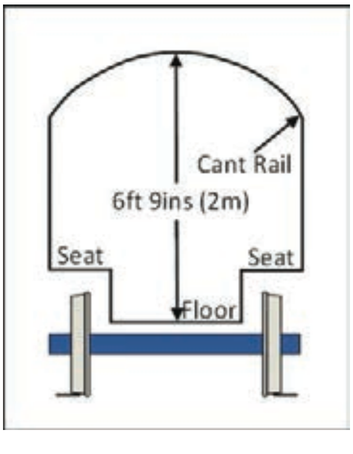


Figure 33: Schematic outline of C&SLR car showing the spatial relationship between the wheels and car body and how sufficient room was provided for passengers to stand up by sinking the floor as low as it could go. Drawing by author.

The centre part of the car floor was sunk between the wheels to provide a narrow gangway about 3 ft. wide (1150 mm) down the centre of the car. This gave about 6 ft. 9 ins (2 m) headroom. The two higher sections of the floor, raised to give enough clearance for the wheels to negotiate the sharp curves, became longitudinal seats, in a style provided on early horse buses. The angle of rotation for the bogies could be up to 10° from the centre line.

The need to allow the wheels to intrude into the floor space remains a feature of tube car body design to the present day, even though tunnels have widened to a maximum of 12 ft. (3.5 m) in some places and wheel diameters are now 700 to 800 mm (Neil, 2016).

The body cross section precluded side doors, so passengers had to access cars through the ends. For the original 3-car formation, there were only two entrances. The design of the entrances was such that the outer ends of the set could not be used by passengers, so only the middle car had entrances at either end. The entrances were cleverly designed as open platforms built as discrete units placed between the car ends and resting on specially constructed, semi-circular extensions to the bogie frames. The platform sides were protected by collapsible, sliding, diamond lattice gates similar to a type supplied by a company called ‘Bostwick’ (Figure 34). They were commonly used for lifts and station entrances. A man at each platform operated the gates.

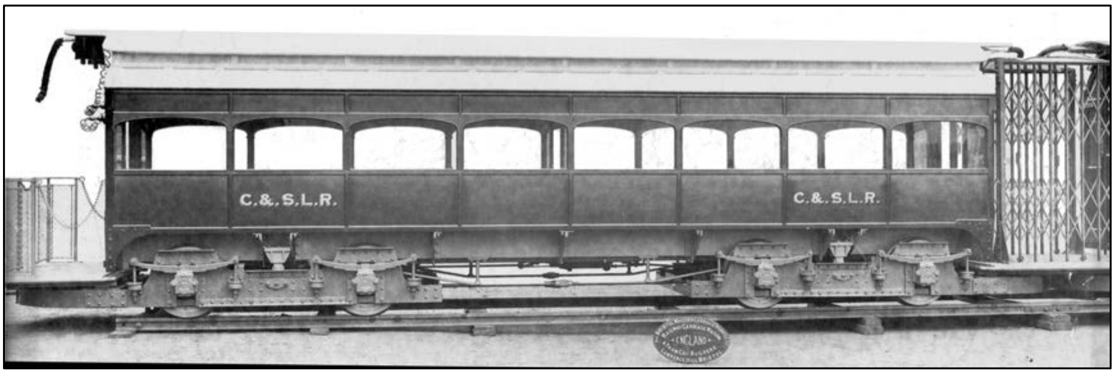


Figure 34: Official photo of a C&SLR car built by the Bristol Wagon & Carriage Works Co. Ltd. in 1901. It shows the underframe construction where the main longitudes are fitted between the wheels. The support brackets for the seating base can be seen placed at intervals along the longitudes. Note how the end platforms are fitted over extensions to the bogie frames. The ‘Bostwick type’ sliding entrance gates can be seen at the right hand end in this view. Author’s collection.

7.3 Early MU Cars

As described in earlier chapters, both the W&C and Central London railways adopted motor cars with a duplex floor design to get the required clearance over the motor bogies. They also had to allow trailer wheels to intrude through the passenger floor with longitudinal seats placed over them to cover the openings.

Transverse seats were provided where there was room for them – away from entrances and bogies - with longitudinal seats fitted over the bogies. This allowed a seating plan for the car which rather quickly demonstrated the usefulness of more free floor space near the car exits. The wider clear floor area at the trailing end bogie allowed some standing room for passengers near the end exit – a feature which originally appeared in US elevated railway cars to encourage passengers to leave quickly and which came to London almost accidentally, as it were, but which proved equally useful on the busier lines in future years.

An unusual feature of the W&C motor car, which really was the first tube driving motor car, was that it used the one-piece entrance platform system copied from the C&SLR. It also had side access doors (one each side) for passengers. W&C trailer cars did not have them and other tube car designs did not adopt them until 1914 (LER, 1914).

Suggestions for freeing up the floor space by using very small diameter wheels have appeared from time to time but there are numerous difficulties with this, notably the reduced ability of the smaller wheel (and its bogie) to manage the combination of weight and stress involved in carrying the vehicle and the safe guidance of the smaller flange profile through point and crossing work. There is also the problem of getting the motors down to a suitable size – more on which later. With the lack of a suitable solution, the wheel intrusion remains to this day with the result that longitudinal seating always has to be provided at the intrusion areas and that this area is not suitable for doors. On the Central London and most subsequent tube cars, transverse seats could only be accommodated in the section between the two bogies.

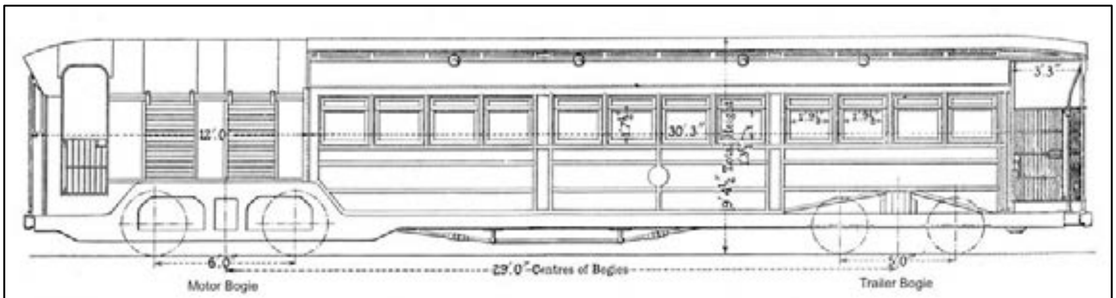


Figure 35: Central London Motor car as built in 1903, taken from a drawing published at the time. The four main sections of cab, switch compartment, passenger saloon and entrance platform were derived from the Waterloo and City motor car design and were subsequently adopted by the other Tube railways. Dawson, 1909.

The production version CLR motor car (Figure 35) had a 12-foot cab and switch compartment section at the front end, on the raised floor over the motor bogie, a passenger saloon 33ft 3ins long and the standard 3ft 3inch entrance platform at the rear end only. David Jenkinson (1996, p. 415), in his book 'British Railway

Carriages', rather ungraciously describes the switch compartment as "a tin tabernacle". Whilst perhaps being a little unkind, he was right in that it did have the look of a rush job (which it was) and that the subsequent LER gate stock designs were "far more cheerful-looking" (Jenkinson, 1996, p. 416).

At the cab end, there were steps down from the switch compartment to the cab floor. The cab floor level was the same as that of the passenger saloon. It had to be to allow the driver to stand. It was a curious feature of Underground operation that drivers often stood when driving, something rarely seen now on main lines in this country. On the Central London, this was because cab seats were not originally provided but they were on other lines and eventually on the Central London. The author found driving was more difficult when standing because the glazing of the cab windows of tube stock was not high enough to give a clear view forward unless the driver of average height stooped slightly, doubtless the reason for the addition of seats on the CLR cars.

The CLR motor car was a mixture of wood and steel (Dawson, 1909 pp 346-350). At the insistence of the Board of Trade, steel was used in the areas where electrical equipment was located but wood was still tolerated for passenger areas. Steel construction was not yet generally accepted for car body design at the time, it being publicly announced that the drumming noise caused by a steel body would make travel very uncomfortable for passengers, even in vehicles travelling above ground, let alone in tube tunnels. This was actually a smokescreen, since most car body manufacturers were basically still operating as horse-drawn coach-builders and did not have the skills to turn out production runs of steel bodies and, if they had tried to develop them independently, they would have priced themselves out of the market. Many operators were also concerned that car weights would rise and would thus increase power consumption. However, some of the more progressive operators of underground lines in the US and Britain saw the opportunity to reduce fire risk with a steel body and to increase car interior dimensions within a tight structure gauge.

Britain was ahead of the US in the move towards steel construction. In 1902 the Central London decided to buy six trailer cars with all steel bodies from the Birmingham Railway Carriage & Wagon Co. and these were delivered in mid-1903 at the same time as the new motor cars (Bruce & Croome, 1996, p 16). They were the first steel-bodied passenger cars built in Britain and, as far as it has been possible to determine, in the world. All tube cars were henceforth built with steel bodies until the arrival of aluminium in the 1950s.

7.4 LER Cars

Following the success of the Central London trial steel trailer cars, the Bakerloo, Hampstead and Piccadilly lines (known as the London Electric Railway (LER) from 1910) all went for steel-bodied cars. The Bakerloo was the first, copying the original Central London experimental motor car design with a short switch compartment (UERL, 1906 Drawing C227), which measured 10ft 6ins including the driver's cab. Indeed, Jackson & Croome in “Rails Through the Clay” (1993, p.92), record that Granville C. Cunningham, the Central London’s general manager, acted as advisor to the Bakerloo. What the UERL did not know at the time was that the CLR switch compartment was too small and that experience had shown that it was necessary to increase the space for the electrical equipment, as was done for the production CLR cars. Later LER cars were also built with a longer switch compartment.

By 1907, all the Underground lines in London, including the District but with the notable exception of the Metropolitan Railway, had accepted the steel body as the way forward for car construction. The reason for the Metropolitan's resistance to this change is not recorded but it was no doubt based on their traditional approach to coach building, to fears about first cost and to the company's penchant for changing the bodywork layouts of cars to adapt to traffic needs. Had the bodies been built of steel, this sort of work would have been beyond the capabilities of the company's own workshop at Neasden and they would have had to outsource it or buy new vehicles to cope with changing traffic requirements. From the benefit of our historical perspective, we could not now criticise the Met. for this decision, since the LER was to run into trouble in the early 1920s when it wanted to add additional doorways to its steel cars. Not possessing the skills to do it themselves, they outsourced the work to Cammell Laird and Gloucester but they found the business so lengthy and expensive (Birkbeck, 1980) they eventually decided to purchase new cars (the Standard Stock) when traffic conditions forced an increase in car doorway requirements.

7.5 More Doors

The standard US style main line car layout, having a single, full length passenger saloon with entrances at the ends, was adopted by most of the London Underground companies for their initial electric fleets. This arrangement was based on the idea that lines ran from the suburbs into the city centre and that, at each station in the mornings, passengers would almost entirely be boarding and that this would be the pattern until the train reached the in-town terminus, where it would disgorge all the collected passengers in one go. The long dwell time that this generated was required for the crew change ends anyway so it had little effect on the service performance. End entrances were thus regarded as perfectly adequate for this sort of operation.

As urban lines were extended and became cross-town links in large cities like New York and Boston, this pattern of operation changed. There was now a substantial boarding and alighting traffic at many consecutive central area stations and it quickly became obvious that the end entrance arrangements could not cope. Dwell times became extended and journey times lengthened. The issue was resolved, at least for the time being, by cutting a centre doorway into the passenger saloon. The idea had been first tried in New York City on the Manhattan elevated line in 1875 (Sansone, 2004) and later in Boston, from where it was imported into London for the District Railway's new electric cars, which had the feature as part of their original design. It was not provided on the Metropolitan's cars as built, nor on any of the tube lines. As most of these routes were built as cross-town links, this was soon recognised as a mistake and experiments with middle doorways started as early as 1911, only a few years after electrification (Jackson & Croome, 1993, p. 93).

7.6 Early Doors

The District, on the other hand, was a pioneer in the provision of centre doors. They also pioneered powered doors in London, which were provided on the District’s new B Stock in 1905 (Figure 36). The doors were controlled from the car ends by ‘gatemen’ who manipulated valves attached to the outside of the car body ends at waist level. The gateman stood between the cars and operated half the doors on the cars either side of his position. There was no positive detection to see that all doors were closed before starting the train, the gatemen just looking to see if they were shut (if they could see) and then passing the OK signal from car to car along the train (Connor, 1981, pp. 12-13).

Figure 36: 4-car unit of District Railway 1905 B Stock at Ealing Broadway about 1909 after its conversion to hand-worked doors. This stock was fitted with air powered doors when delivered but these were poorly designed and slammed shut, trapping people and clothing and causing injuries. They had brass edges instead of the rubber edges used today. The conversion to hand operated doors took place during 1908. Collection: B.R. Hardy.

The use of powered doors was, in the author’s view, because it was necessary to find a way of closing the doors using one person per car, hence the power operation. Each door leaf was operated by a pair of horizontal cylinders mounted at the top. Control was directly through the gateman's valves. There was one valve for each door leaf. Air entered one cylinder to open the door and the other to close it as required. Unfortunately, the system was not a success. The door operation was quick but crude. There was no anti-slam system and the closure action was rough on anyone who got caught in it because the door edges were finished in bronze, not rubber as they are today. There were soon claims for injury and torn clothing and they got to be so common that they were giving the District a bad press (The Times, 1908).

A further problem with the system was that an attempt was made to regulate the use of the doors. End doors were reserved for boarding passengers while the middle doors were used as an exit – well, that was theory. But, it did not work. Philip Dawson, in his book 'Electric Traction on Railways' (1909, p. 285), wrote, "*Unfortunately, experience has shown that it is very rarely possible to train passengers in this fashion, particularly at rush hours when it is most necessary*". Although notices were placed over the doors to show which was for entrance and which for exit, people just did not bother with them, even if they read them.

In the end, the District gave it all up. The air system maintenance was expensive and the bad public relations was unlikely to be helping the share price or ticket sales. The air operation was withdrawn in 1908 and the doors converted to hand operation so that passengers could use them as they wished (MDR, 1908). Apart from a few experiments on a car in 1916 (MDR, 1916), the District did not see air operated doors again until 1937. It was left to the tube lines to develop them.

The tube lines also quickly realised that they had to improve the door service if they were to maintain service quality and keep up with the demand. Although a bodyside door had been designed into the W&C motor cars of 1898, it required an attendant to close it before the train could be dispatched. This was not too difficult on a line with only two stations that were both terminals but there must have been some apprehension at how this might be done on the much longer new tube lines.

It is worth mentioning at this point that, at the time of their opening, all the Underground lines employed a man on each car to operate the entrance gates. The standard arrangement on a 6-car train was: Driver, Front Guard, three intermediate Gatemen and a Rear Guard. The guards and gatemen stood at the coupling position between cars and operated the gates on either side (Jackson & Croome, 1993, pp. 95-96). Working a central doorway as well would have required some sort of remote operation. The District solved the problem by introducing air-operated doors, of which more later (see section 6.13), but the tube lines did not develop such a system that would fit their car body profile. It just seems to have been too difficult.

With only a few years of operational experience, it was realised that adequate door service was crucial to the successful operation of a rapid transit railway and the Underground looked for ways to improve it. The provision of more doorways was a solution but, although this meant that seats would be sacrificed, it did not really matter. The average journey time was (and still is) only about ten minutes over much of the system so standing time was not considered an issue. Dwell time – the amount of time spent at stations boarding and alighting – is much more important and lots of wide doorways are essential to keep it short. This was a lesson learned very early on in the game and one that is just as important today.

Figure 37: One of two Leeds Forge-built motor cars delivered to the Bakerloo in 1915, seen here in the yard at London Road depot. The car has several new developments in its design. The clerestory roof has been replaced by an arched roof to reduce complaints of the cold in winter; a 3'-2" wide opening has been cut into the car body to allow a centre entrance doorway and the traction control has automatic acceleration. Photo: LT Museum.

It appears that some experimental conversion work on the fitting of centre doors was carried out in 1912 on the Piccadilly Line (Jackson & Croome, 1993, p. 116) but there is no detail on what was done and it was only in 1914 that new cars appeared on the Bakerloo with centre doors (Figure 37). The design was a single person width, automatically closing, inward-swinging, hinged door with a remote locking system operated from the gateman's position. It was far from satisfactory but it was at least some relief for passengers trying to get off a motor car where there was previously only one exit.

7.7 Doors - Swing or Slide?

The introduction of centre doors on tube cars was not without its problems. A section through a typical tube car body shows that the height of the bodyside between the car floor and the cant rail is only about 5ft 6ins, compared with 6ft 9ins on a surface stock car. This meant that the top of a door positioned in the bodyside was too low to be comfortable for most passengers getting on and off the train. The answer was to set the door back into the car and to cut away a section of the roof to accommodate the height required. The door was hinged because, at the time, no one could see a way of making a sliding door fit in this arrangement without using up a lot of the car interior. It also had to be partly automated because the gateman was located on the end platform to work the gates and did not have the time to fight his way through a crowd of passengers to open it. For safety, it was locked between stations but the gateman released the lock automatically when he opened the gate at the car end (Jackson & Croome, 1993, p. 116). Passengers had to open the door themselves but it was fitted with a self-closing mechanism so that it would swing shut when released. It was re-locked automatically when the gateman shut his gate.

In 1915, 24 new motor cars were ordered by the CLR for their Ealing extension (Jackson & Croome, 1993, p. 128). They marked a further step in tube car development with the enclosure of the end platforms. The gates were gone, replaced by swing doors but these were still operated by a gateman. The middle door arrangements were virtually the same as the 1914 cars.

In 1920, two further additions to the tube car fleet were delivered - the Watford Joint Stock (WJS) and the Cammell Laird Stock (Thomas, 1928). The Cammell Laird Stock, a batch of twenty trailers and twenty control trailers ordered for the Piccadilly Line, presented the next stage of development in the tube car body with the introduction of air operated sliding doors (Prigmore, & Shaw, 1970). Perhaps because they were a small batch of cars, they were not always appreciated for the significant step in progress they represented. The new door system offered both better station dwell times and a reduction in staffing requirements. The height problem had been solved by shaping the doors to match the bodyside and roof, thus part of the roof became part of the doorway. Because the doors were sliding instead of hinged, they did not intrude into the passenger areas in the way that the inward opening gates and hinged doors did. It was difficult to get a gate or door open against the weight of passengers attempting to get off so the sliding door was the perfect solution. Even better, the doors could be operated remotely, so it was no longer necessary to have a man on every car. The typical 6-car train went from a 6-man crew if it had gates to a 3-man crew if it had air doors.

Figure 38: A total of 10 x 6-car trains with pneumatically operated siding doors were introduced on to the Piccadilly Line in the early 1920s. The motor cars were converted from 1906-built stock while new 40 trailers and control trailers were supplied by Cammell Laird. This is one of the new trailers. The central doorway pillar is clearly shown. Photo: LT Museum.

7.8 Motor Car Conversions

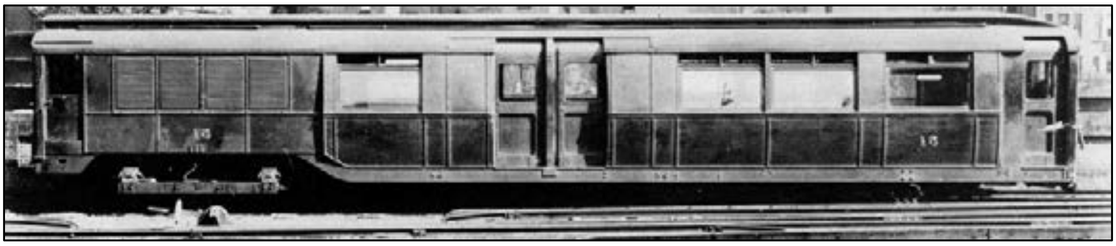


Figure 39: Piccadilly line motor car No. 18 in Lillie Bridge depot. This car was originally built in 1906 as Gate Stock. It was one of two cars converted to air door operation by Cammell Laird in 1921. They were provided with a double doorway cut into the centre of the car while the end platform was enclosed and provided with remote door controls for the guard. It doubled as a passenger entrance when the guard was not in residence. Another 18 cars were converted by Gloucester but they had single central doors. A batch of 40 new trailers and control trailers was built by Cammell Laird to run with these cars. Photo: LT Museum.

The motor cars to work the new Cammell Laird stock were converted from existing Piccadilly Gate Stock motor cars. Two cars were sent to Cammell Laird's factory in Nottingham, where they were fitted with double centre sliding doors and a trailing end door in an arrangement similar to their new trailer cars (Figure 39). Another 18 cars were sent to the Gloucester Railway Carriage & Wagon Co. but these had single sliding doors in the centre (GNPB, 1923). It is not now evident why the double door idea was abandoned on the motor cars when it was provided on the new trailers. Perhaps it was because the wide opening in the car body required for the double doors caused a weakness in the structure but this was apparently solved with a pillar in the middle of the double doorway. More likely, it was thought that the wide doorways took too many seat spaces, so the single door was accepted as the preferred option.

The conversion work done by Cammell Laird and Gloucester was time consuming and difficult. The work was outsourced by the Underground because the group did not have space in their existing facilities. Lines did their own maintenance and overhaul work and this was increasing with the size and age of the fleet, so there was no room for conversion work. In 1980, the author met Cyril Birkbeck, who was an Underground apprentice at the time of the conversion work and he told of how he was sent to Gloucester in 1920 to gain experience. He was the assistant to the Underground engineer responsible for the design work, R.G. Sharpe. Cyril described the slowness of the job and the constant stoppages due to design problems and shortages of men and materials. He said that the bodies were most unsuitable for the conversion. Also, few of the people at Gloucester had worked on all-steel bodies before. Most of them were carpenters and they had little idea of what to expect. He came back with the message that, next time, it would be better to "*do it ourselves*" (Birkbeck, 1980).

With the introduction of the 1920 Cammell Laird Stock, remotely controlled sliding doors became standard for the Underground. More doorways were added for trailers in future designs but the motor car set up was pretty well fixed for the next 15 years with doorways at the centre and rear of the car. With this new feature, the struggle to get station dwell times stabilised had now turned the corner. It only remained now to find a way of reducing the size of the traction equipment so that it could fit below the floor and free all the above-floor space on motor cars for passengers like surface cars. This came in the mid-1930s with the 1936 Tube Stock.

Figure 40: A Bakerloo train at the northbound platform at Waterloo in 1936. The car in the foreground is one of the batch of 40 cars built by Cammell Laird in 1920. The view shows the extreme platform curve at this station. Exhortations to "Mind The Gap" are nothing new (expect perhaps the additional word "Please") and an illuminated 'Beware of Gap' sign hanging from the platform ceiling is also designed to make passengers aware of this problem, together with under platform lights that lit automatically as the train arrived. Photo: LT Museum.

7.9 New Standard Stock

An ambitious programme for the updating and expansion of the C&SLR was planned immediately after the end of the First World War in 1918 (Jackson & Croome, 1983, pp. 132-133). It involved the rebuilding of the existing line to standard tube tunnel dimensions, connecting it to the Hampstead line at Euston and extending south to Morden and buying new stock to run over the extensions. Six ‘sample’ tube cars were built in 1922 to a single basic body configuration (LPTB, 1935). All the cars were trailers, apart from one control trailer. The details of construction and interior fittings were left to the manufacturers but the body layout and door positions in particular, were specified by the Underground. The big change from the previous design – the Cammell Laird Stock – was the provision of two double doorways per car side instead of one double door and two singles. The two double doors provided a wider opening than two single doors. The single doors on the Cammell Laird cars were rather narrow at a less than 2ft opening but the Standard Stock double doorway was 4ft 6in wide, giving more than a foot of extra opening width per car (LPTB 1935). The Cammell Laird end doors were narrow because they were squeezed, with the door engine, in between the car ends and the wheel box protecting the bogie. The double doors were also somewhat restricted by a stiffening pillar positioned midway in the opening so that the two doors were separated. The double doors on the new cars had no pillar.

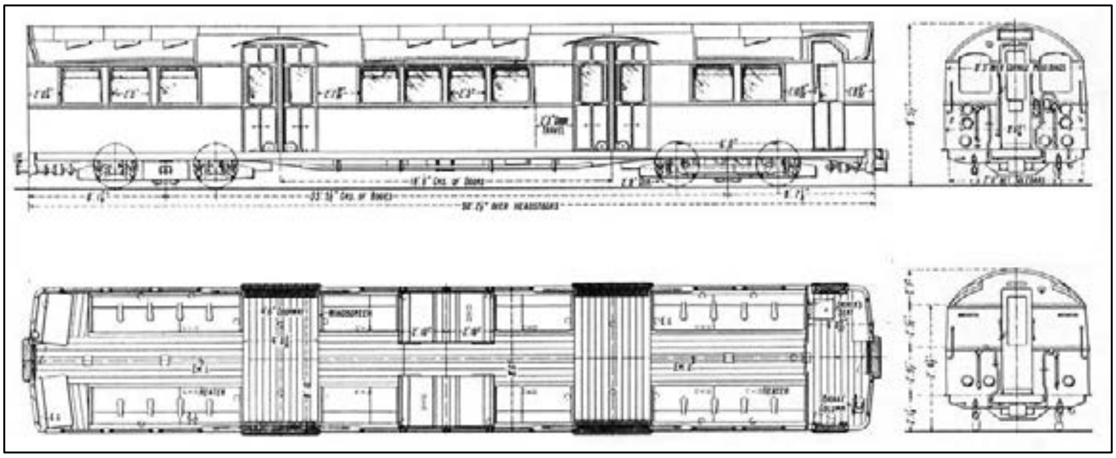


Figure 41: General arrangement of 1923 Standard Stock control trailer car built by Cammell Laird. The car was still the standard 50ft long but it had two double doorways each offering a clear 4ft 6in opening. This general design was used on all batches of new tube trailer cars up to 1930. Collection: Author.

The sample cars entered service on the Piccadilly Line in 1922, coupled between pairs of the recently converted Gate Stock motor cars. They were generally regarded as successful and were soon transferred to the Hampstead Line for tests on the newly opened Edgware extension. Most of the more outlandish furnishings, ranging from mock Georgian upholstery to mock Victorian lampshades, which were offered by the various manufacturers, were ditched in favour of the Underground's own design, which was plain and functional and was embodied in the sample control trailer built by Gloucester. The design, both internal and external, remained the standard for several batches of cars ordered between 1923 and 1930.

Motor cars to match the new Standard Stock trailers were based on the design of the Cammell Laird converted Gate Stock cars with double doors in the car centre separated by a central pillar (Figure 42). The difference here was that the end door of the new cars was not sliding but hinged and it was only used by the guard. As mentioned above, at this time there was a guard at each end of a standard 6-car train, controlling the doors on his half of the train (formed M-T-CT) so his doorway would not be used by passengers. They had only the centre doorway.

The logic behind this decision was, in the author’s view, because it was cheaper not to fit a door engine and controls to the doors at the guard’s positions since, at the busiest times when full length trains were running, guards occupied these positions at both ends of the train. If a 3-car train was operated, the guard was originally located in the control trailer cab when the motor car was leading, so the control trailer cab had to be provided with door controls too. The doors of the unused guard's position at the rear of the motor car were locked out of use. There was little need for more than one passenger doorway on the motor car since the trains were running in the short formations only during off-peak periods.

There were detail bodywork variations in the batches over the years up to 1930 (Hardy, 1986) but the most significant was the removal of the central pillar in the doorways of the 1929 order (Hardy, 1986, p. 46). The removal of this obstruction further improved the loading/unloading times.

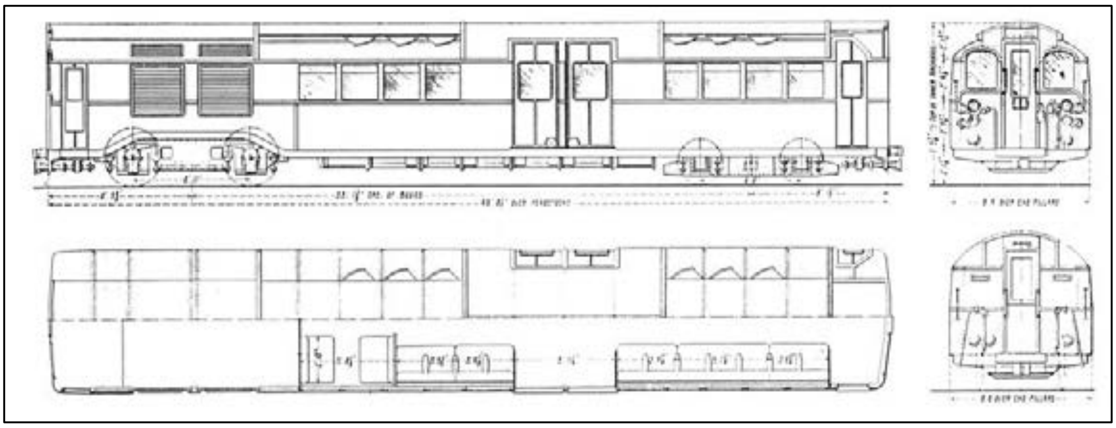


Figure 42: General arrangement of 1925 Cammell Laird-built Standard Stock motor car. All motor cars of the 1923 to 1928 period were built to this profile and had a pair of central double doors divided by a structural pillar. The first batch of cars to appear without the central pillar was built in 1929. The trailing end was used only by the guard, who was provided with a hinged door, which was locked when out of use. Note the mostly longitudinal seating layout. Collection: Author.

7.10 Central London Conversions

The huge operational advantages of remotely controlled, powered, sliding doors led to a search for ways of getting them on every tube line as quickly as possible. The two options were replacement or conversion, with conversion as the preferred choice as it was thought to be cheaper. Conversion meant enclosing the gate entrances of existing cars and altering the bodysides and roof to take sliding doors. The roof of the older cars was a particular problem because it had the clerestory down its centre and the side sections had a rather flat profile. This would make the top of a door curve inwards very sharply. The problem was resolved on new vehicles by arching the roof at doorway positions.

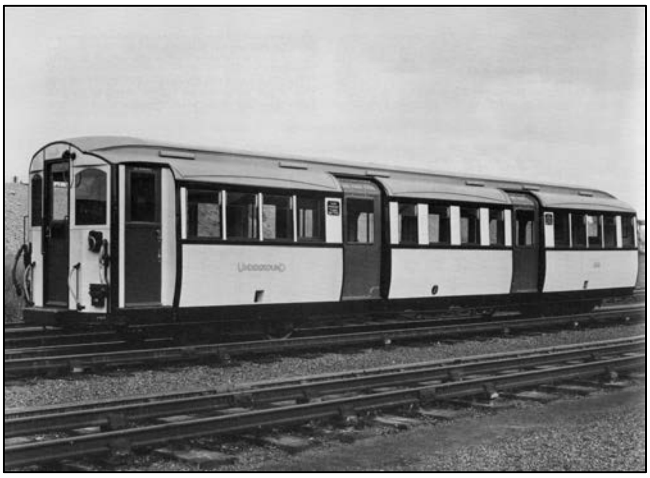


Figure 43: A CLR control trailer car after its conversion to air operated doors. The end platforms were fully enclosed and two single doorways were cut into each body side. The conversion of these wooden-bodied cars was much easier than for the steel-bodied LER cars. The doors were controlled through a compressed air control pipe operated from the guard's position by a special valve, rather like a brake valve. Collection: Author.

The Central London was an early target because most of stock had wooden bodies and could be converted comparatively easily. One trailer was experimentally done in 1925. It had the gate ends enclosed and single doorways cut into the body sides at roughly one third and two thirds distance along the length, in a design similar to one of the proposals put forward, and then rejected, for the Cammell Laird Stock in 1919. The experimental car was tested in service on the Central London and worked well enough, so the whole fleet was converted at Feltham (Figure 43) (Electric Railway Journal, 1926, p. 1050).

The steel Gate Stock of the LER lines was also examined for its conversion possibilities. There was some tinkering with various cars over the next three years when several were sent for experimental conversions at Feltham and Birmingham but, by this time, the stock had over 20 years in service and was showing signs of its age. The technology was outmoded, with old traction motors, manual acceleration, Westinghouse air brakes and open end entrances. The need for improved traction and braking performance and the huge savings accruing from the elimination of gatemen - meant that Gate Stock replacement was viable financially. At first it was proposed that only car bodies would be replaced and that electrical equipment would be salvaged from the gate stock. A similar process had been chosen by the District when it bought new motor car bodies and fitted them with traction equipment from old bodies in the early 1920s but this idea was soon discarded by the LER in favour of complete replacement with new motors and control gear (LER, 1927). Deliveries of replacement Standard Stock began in 1928 and were completed in 1930.

7.11 Longer Bodies

The pressure for improvements to tube car body design was unrelenting throughout the 1920s. The need to increase capacity to cope with the rising traffic levels generated by the Hampstead and C&SLR extensions to Edgware and Morden and the plans to extend other lines, pushed the Underground towards more radical car body design solutions. There was the need to keep dwell times down by providing lots of doors and by the need to squeeze in as many people as possible. There was little space available and what there was had to be maximised. Both these factors led to a push for longer cars.

Figure 44: A trailer of Standard Stock built in 1931, seen in new condition at Ealing Common depot. The 1931 and 1934 batches of this stock, built for the Piccadilly Line, were longer than the earlier versions and the trailers had single end doors added. The body ends were slightly tapered to allow the longer cars to negotiate the tight curves on some of the tunnel sections. Photo: LT Museum.

The combination of a single track, small diameter tunnel and some sharp curves meant that the LER tube car was basically restricted to a 50ft length and 8ft 8in width. Any lengthening of the body would force a narrowing of the width so it could still get round the sharp corners at places like South Kensington and Piccadilly Circus. Narrowing the width throughout the car length was not considered ideal so a compromise solution was implemented where the width was retained but the length was increased by tapering the car ends inwards so that the structure gauge would not be infringed. The taper was very subtle, almost invisible but it was sufficient to allow an extra 10ins at each end of the vehicle. This extra length provided room for 2ft 3in end doors and their engines to be added whilst allowing the two pairs of double doors to be retained as well. The door service was increased by 30% with this layout (Figure

44). A pair of cars with the design were introduced onto the Piccadilly Line in 1930 as part of an experimental train being trialled before a bulk order was placed for new stock to work the extensions to Cockfosters, Hounslow and Uxbridge (Hardy, 1986, p. 48).

The experimental train comprised two motor cars and four trailers. Two of the trailers had the additional end doors but the other two retained the existing two double door arrangement but they were widened to 5ft 3ins in place of the 4ft 6ins of the older cars. Some observations on the efficiency of both types seems to have been done when this train entered service and it must have become obvious that more doors rather than wider doors was the answer. All subsequent tube cars were provided with end doors, so these two prototype cars provided a template for all tube cars built since. The design, which has been perpetuated for the 2009 Tube Stock for the Victoria Line (built 2008-11), will last for over 100 years.

More than 40 years after it first appeared, the tapered body concept was developed further on the 1973 Tube Stock, when the 52ft car was stretched to give a 58ft car (Figure 45). Improved geometry for the setting of the bogie centres, the overhang of the body ends, the suspension and the extended tapering of the body shell allowed the extra length without loss of width. It also allowed a 6-car train formation to replace the 7-car formation used on most tube lines from the mid-1930s.

Figure 45: A Piccadilly Line 1973 Tube Stock car, showing the extended tapered car ends that allow longer cars round the tight curves in tube tunnels. This train is at Ealing Broadway (District), working a special service in connection with engineering works in December 2013. Photo: Kim Rennie.

The new 6-car ’73 Stock train was 17ft shorter than the older 7-car type. This gave a reduction in capacity of about 5%, not what the passenger might think is desirable at 08:15 in the morning between South Kensington and Knightsbridge (the busiest section of the Piccadilly Line) but the number of passenger journeys in London had been falling almost every year for the previous 20 years (Chymera, 2014) and it was already more than 10% down in real terms. Logic dictated that capacity could be reduced without increasing the discomfort for passengers.

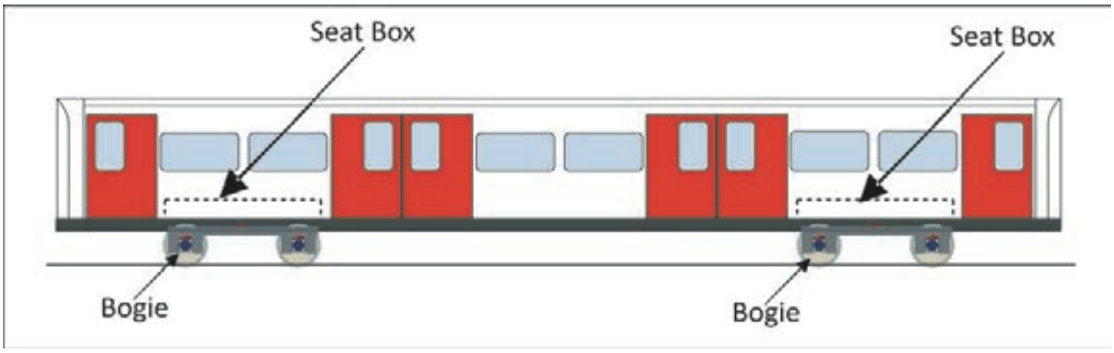


Figure 46: Schematic outline of modern tube car demonstrating the spatial relationship between the wheels and car body. It also demonstrates the limits for the provision of doorways. The doorways cannot be positioned where the wheels protrude through openings in the car body underframe. The openings are protected by the seat box built over them. This means that all tube cars built to date have to have longitudinal seats over the bogies. Drawing by Author.

7.12 Wrong Footed

The trend towards minimalism for rolling stock design on the Underground continued to the mid 1980s. Fleets were reduced in size and train design reflected a belief that traffic would continue to fall and that equipment could be reduced accordingly. When new stock was designed for the District line in the late 1970s, the long car philosophy introduced on the Piccadilly line was continued. The D78 Stock, as the new fleet was known, was a surface stock version of the 1973 Tube Stock, both in form and equipment. The only major difference was in the door arrangement. Each car had four single-leaf doors on each side (

Figure *47*). The doors were only 1200mm wide but this was thought sufficient in an era of diminishing loadings. A single-leaf door design was also introduced on some new tube cars bought a few years later, the 1983 Tube Stock. It proved to be a mistake.

In 1981-3, a series of political and legal manoeuvres (Carvel, 1983) resulted in fares on the London Underground being reduced and in the introduction of a ‘Travelcard’, allowing the purchaser to travel unlimited trips within a zone without additional payment. These Travelcards also became attached to commuters’ season tickets, allowing additional lunchtime or evening trips at no extra cost (Grayling & Glaister, 2000, pp 9-10). Despite London Transport's attempts to restrict this initiative, on the basis that it had been downsizing for years and that it no longer had the resources, materially or staff-wise to cope with the predicted traffic increases, it was pushed ahead by the ruling political regime and it resulted in an explosion of additional travel. The Underground was completely wrong-footed and began a rapid back-pedalling in their rolling stock policy, even having to re-instate trains already withdrawn from service for scrapping (Connor, 1989, p. 114). Ever since, the Underground has been struggling to cope with ever increasing traffic levels and has had to relearn the skills needed to cope with large numbers of passengers under both normal and disrupted conditions.

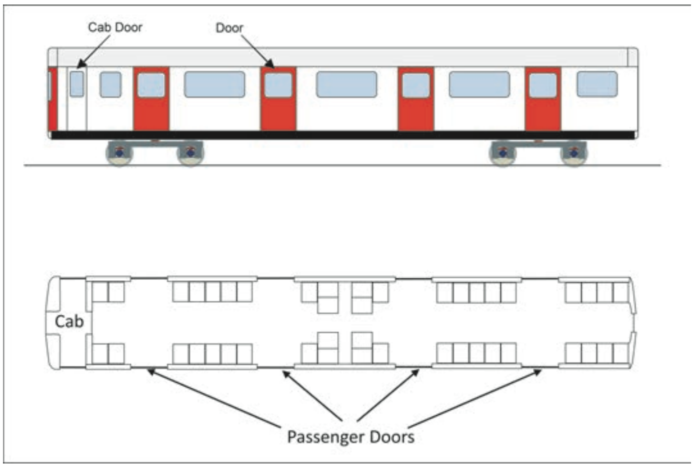


Figure 47: Schematic of the District line D78 Stock showing the seating plan of a motor car and the positions of the single leaf 1200mm doorways introduced with this stock. This allowed half the number of door engines compared with the C Stock then being used on the Circle and Hammersmith lines. Drawing: Author.

7.13 Recycling

The first air-doored tube stock, the 1920 Cammell Laird Stock was fitted with recycling doors, i.e. the doors re-opened if they struck anything while they were closing. The idea that passengers should be protected against being hit by closing doors was firmly embedded in the corporate mind after the difficult experiences on the District in 1905-8. Recycling doors seemed to offer an excellent solution.

Engineering drawings seen by the author in the 1980s (since believed lost in a flood) and described in his book, Air Door Equipment on the London Underground Train (Connor, 1981, Pp. 15-17), showed that each door leaf was fitted with a sensitive leading edge as described by Collins (1945). The edge consisted of a 3½-inch deep canvas cover fitted over a vertical rod. The rod was linked, through the waist of the door, to a reversing valve mounted over the door engine. If the rod was struck, the action of the door engine was reversed and the door would immediately re-open.

As is sometimes the result of such innovative ideas, whilst theory was excellent, it soon presented serious problems in the execution. To begin with, the equipment was mechanical, complicated and unreliable and then passengers quickly discovered its major weakness. They could prevent door closing by using the system to wait for lagging friends and sundry latecomers, especially if the latecomer happened to be an attractive lady. A simple tap on the door edge as it closed would allow it to reopen, thus securing the gratitude of the lady in question and affirming your status as a gentleman - admirable behaviour in polite society but disastrous for the operator trying to run a high density urban railway service.

Delays to the train soon became endemic and the recycling system was quickly abandoned and replaced by rubber door edges and sprung arms as described above. The name ‘sensitive edge’ however, has stuck and remains to this day.

Until recently, recycling has remained dormant but it was re-awakened for the recent Bombardier-built stocks on the Victoria and Sub-Surface lines under what is sometimes described as ‘intelligent’ door control. A door trying to close will retract slightly if it hits an obstruction and then it will try to re-close. This happens three times, after which the door will close. The stocks also have an anti-dragging system. If pressure on the door edge from a dragging object or person could be detected, an electronic signal provides an emergency brake application. Teething troubles and reliability soon became an issue, particularly on the 2009 Tube Stock. After extensive modifications, in which the author was involved, the system seems to have settled down to a more reliable level.

7.14 Surface Stock Bodies

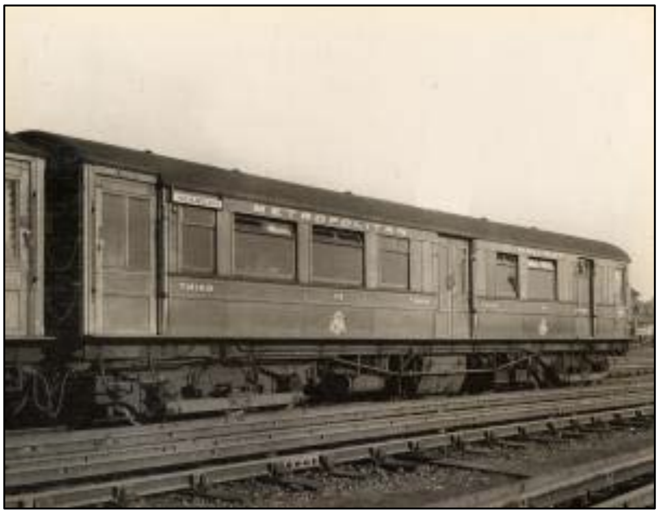


Figure 48: Metropolitan Railway driving motor car introduced in 1913 as seen at Neasden in March 1934. Note the centre doors. These cars were equipped with two sets of traction equipment and four traction motors. They were powerful enough to allow an 8-car train to operate with only two motor cars, one at each end. The Metropolitan never normally ran trains with more than two motor cars. Photo: LT Museum.

Surface stock development generally followed the tube car pattern. The original surface stock, without the structural limitations of the tube lines, could have all the traction equipment under the car floors. The design also imported the US style of clerestory roofed body on both the District and Metropolitan Railways. The District, being under the same ownership as the Tube lines, tended to follow a similar development path where possible but the Metropolitan took a different direction. While the District soon adopted steel bodywork, the Met. stayed with the traditional wooden framed body (Figure 48) until 1932, just a couple of years before its takeover by the LPTB. It also split its rolling stock into long distance and short distance types.

The Metropolitan’s first production orders for electric stock consisted of saloon-type cars with open, gated end platforms (Benest, 1964, p. 53). They were very similar to the original Sprague-equipped cars built for the Chicago South Side Elevated. Later batches had enclosed ends and the earlier ones were converted to match to overcome complaints of cold and draughts. Unlike the District, centre doors were not provided at first. This proved to be a mistake and the Metropolitan began fitting additional doors into existing cars from 1911 (Benest, 1964, p. 90). There were a couple of trials with different door sizes and positions but the final solution was a double-door configuration, similar to the District’s in many respects. They had realised, like the District and Tube lines, that dwell time management was critical and that improvements to the entrance/exit system were essential to this management.

Figure 49: Metropolitan Railway 3rd Class Saloon Stock trailer car no 103 of 1921, as seen at Neasden in March 1934. Like the contemporary District stock of 1920 (The F Stock), this design had three sets of double doors. After 15 years of operating a high volume urban railway, the Underground companies realised that more doors were needed to keep station dwell times down to a reasonable level. Photo: LT Museum

At the time, the Met. used both saloon and compartment stock and some trains were run with a mixture of both. Some people within the organisation were becoming convinced that compartment stock, with swing doors to each compartment, was better at loading and unloading passengers than trains with sliding doors. To test their theory, they introduced swing doors to a set of rebuilt saloon-bodied cars with rearranged seating and put it into service in 1919, calling it the “Hustle Train” (Benest, 1966, p.150). They were so proud of it they even invited the District and LER management to have a look at it but those who attended the viewing reported back that they did not think it offered any significant benefits over sliding door stock. Evidently, the Met management agreed with them, since their next orders for new cars reverted to sliding doors – with three sets, very similar to the arrangement on the District's F Stock (Figure 49).

During this time, the Met still specified compartment stock for its longer distance services, mostly steam hauled. When they needed new electric stock following the opening of the Watford branch and the extension of electrification to Rickmansworth, they went for compartment stock, which was eventually to become known as the T Stock (Bruce, 1983, pp. 72-75). They knew that their long distance passengers preferred compartments and lots of seats but that passengers on the inner suburban and Circle services would have to put up with saloon stock having less seats and more standing space if they were to get on the trains at all.

7.15 Footboards and Flares

A feature of all the pre-1936 surface stocks was a wooden footboard mounted along the outside of the bodysides at floor level. It was designed to 'oversail' the platform edge. It was added to the original District Railway cars soon after electrification to prevent accidents where passengers slipped between the platform edge and the car body.

Figure 50: Traditional and modern designs seen at Croxley on the Metropolitan line's Watford branch about 1961. On the left is a compartment type T Stock train of a design originally dating back to 1910 while, on the right is a P Stock train, introduced in the late 1930s. The flared bodyside skirt of the P Stock was designed to replace the footboard of the older designs but to retain a cover over the gap between the train floor and the platform edge. Collection: B.R. Hardy.

Unfortunately, it led to a number of accidents in its own right. Doors were sliding but manually operated by the passengers and they were not locked while the train was moving. Indeed, during the warmer weather, they were often left open to aid ventilation; perhaps not what we would have in mind today as a means of 'cooling the tube'. Back in the days of hand-worked doors, some of the livelier passengers, anxious to catch a departing train, took to jumping onto the footboard and clinging to the door handles while they struggled to open the doors. Occasionally, they fell or were injured when they were hit by the tunnel wall or bits of equipment as the train left the station. If they were spotted, the guard would stop the train, but this would cause a delay. In a novel idea to eliminate these problems, Graff-Baker came up with a scheme which eventually became an icon for rolling stock design.

The idea was to flare out the bottom edge of the door so that it covered the footboard. This made it impossible to stand on the step. The body panels along the rest of the car were flared out to match so that the oversail feature was retained along the whole car and the gap between the train and platform was still protected. A feature was that the bodyside slope at floor level was duplicated at the top of the windows in the covers for the glazed ventilators (Moss, 2000, pp. 68-75). The unique symmetry of this design became a feature of the Underground's surface stock for the next 35 years. The design was provided on 811 vehicles built between 1937 and 1959 and was only superseded by the introduction of the A Stock, with its wider body profile, in the early 1960s (Moss, 2000, pp. 93-95).

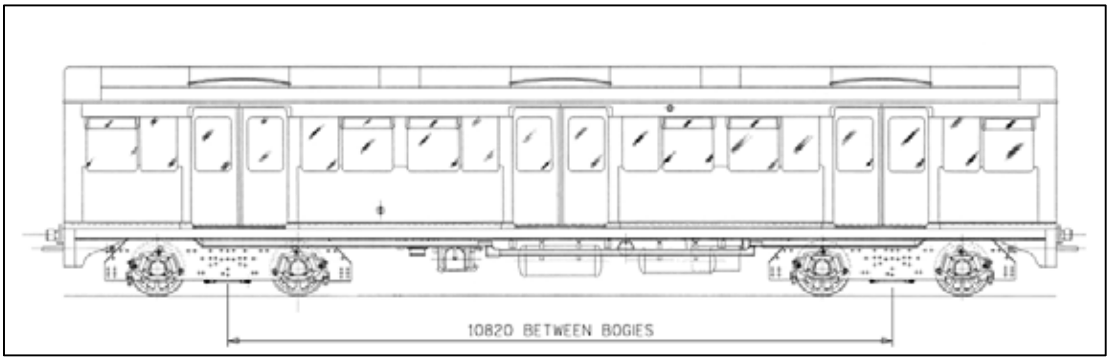


Figure 51: Side elevation of A Stock trailer car of 1960. The three sets of double doors were a return to a 1920s design adopted on both the Metropolitan and District railways. Drawing TfL (2003).

The second generation of sub-surface stock built in the late 1930s were given the same body/door configuration as the contemporary tube cars. This arrangement survived after the second world war until the arrival of the replacement stock for the Metropolitan line known as the A Stock, introduced between 1960 and 1964. Although the driving cars retained the traditional arrangement, the trailer car design reverted to the early 1920 design with three sets of double doors per side (Figure 51). This was followed by the C Stock of 1969 (much disliked by the author for its poor driver amenities and dreadful handling), which had four sets of double doors per car side but on all cars, including the driving cars, which were longer than the trailers as a result.

7.16 Refurbishment

A feature of London Underground rolling stock is longevity. The 1938 Tube Stock lasted almost 50 years in passenger service and the current 1972 Tube Stock on the Bakerloo line is now (2017) 45 years old. The 1972 Stock is currently going through a refurbishment programme to correct structural problems resulting from its age. It is also being modified to comply with Rail Vehicle Accessibility Requirements (RVAR). This project offers an example of the use of historical knowledge to inform the development of the project and to reduce the expected cost of the work.

7.17 Space Train

In the drive to maximise the capacity available on the deep level tube lines, engineers on LU began looking at a concept design for a new tube train that could carry 40% to 45% more passengers within the existing tunnel profile. At the time, the initial view was that the Victoria Line should be tackled first because the 1967 stock was already 30 years old and was earmarked for replacement within the next 10 years. It was also a stand-alone line, with no service connections with other lines to complicate matters during the replacement phase.

The new train design was called ‘Space Train’ (Moss, 2000, pp. 218-222). The Space Train concept looked to articulation to open out the floor area of the train and to provide open gangways between cars to aid passenger circulation and improve ventilation. The Victoria Line version was to have 12 articulated cars mounted on 13 bogies, giving a train length of 137·6 m. The Victoria Line’s 1967 Stock had a length of 129·8 m for 2 x 4-car units. It was envisaged that, with fully-automatic operation and platform screen doors, it would be possible to fit 24 double-doors, each with a clear opening of 1664 mm, inside the 132·6 m distance available at platforms.

Figure 52: Model of the Underground’s Space Train concept. The idea was to widen the car body shape to match more closely the tunnel diameter. Car bodies were to be articulated with wide car connections. There was also an idea that the positive current collection would be at roof level and the return through the running rails. Photo: London Underground.

Two other important features of the Space Train were the cross sectional shape of the cars and the lower floor. The Space Train was to be wider at the waist level than existing tube cars to more closely match the circular tunnel profile (Figure 52). This made it some 436 mm wider at waist height than existing stock. The floor was to be set low enough to give level access to and from LU's 520 mm high tube platforms. This would have needed some cutting back of platform edges. Much of the increase in floor area was to be obtained by having seats set back to exploit the near-circular cross-section of Space Train.

7.18 Standing Room Only

Space inside metro trains is precious, so careful calculations are used to determine the best layouts in terms of maximising capacity. LU assumes an average of seven standing passengers per square metre (pax/m2) of available floor space. This is made up of 8pax/m2 in the doorway areas and 6pax/m2 in seating areas. Because people do not tend to stand that close to each other because of bags and papers, there is also an ‘observed’ estimate of 5pax/m2. The floor area for standing excludes seats, which are counted separately and 300 mm in front of each seat to allow for feet. As a comparison, loading in Hong Kong’s metro system is calculated at 10pax/m2.

The low floor design was a big part of the Space Train concept. The scheme originated from the idea of a roof-mounted conductor rail, with running rail return, which was to replace the traditional 4-rail traction system. The roof was to be flattened slightly to allow a pantograph to be added and the conductor rail was to be of an inverted light alloy rail with a stainless steel cap fitted within the 200 mm available between train roof and tunnel lining. To accommodate the roof mounted current collection and maintain internal height, the floor had to lowered (Figure 53). The lowering of the floor reduced the space under the cars for motors, wheels, air reservoirs and other equipment. A complete redesign was necessary.

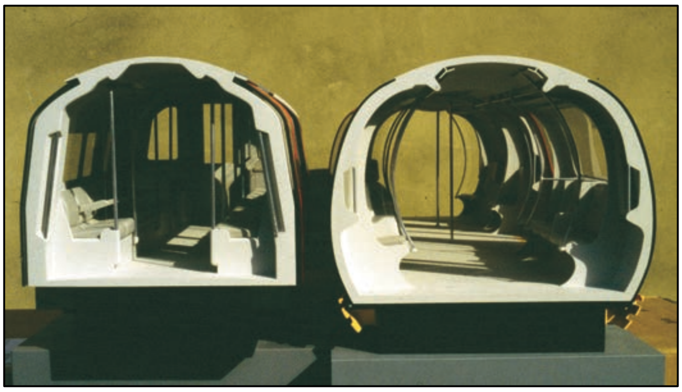


Figure 53: A photo of two models to compare the cross sections of (left) a 1996 Tube Stock car and (right) the Space Train. The body of the Space Train was 218 mm wider than the 1996 Tube Stock. Photo: London Underground.

Some models of the Space Train were produced (Figure 53) but no further work was done after development was killed by the private-public partnership (PPP) proposal announced in March 1998. No one could see a private company, appointed to manage the maintenance and upgrade of the Underground, paying for the development of a new train design that they could not guarantee would meet the capacity and reliability requirements of the PPP contract. Traditional and risk-free design was to be continued while the growing need for improvements and for continued knowledge based development stopped.

7.19 The Siemens Initiative

The PPP scheme was not a success for all sorts of reasons but it was finally killed by the absence of the political will to make it survive and by the shaky financial control exercised by almost everyone who had anything to do with it. In 2008, ten years after the original concept of the PPP and just six years after contracts were first signed, the whole edifice started to collapse when Metronet, the company set up to look after the Bakerloo, Central and Victoria Lines and the sub-surface routes, went into administration and their operation came back under the control of London Underground. Tube Lines, who were responsible for the Jubilee, Northern and Piccadilly Lines, came back into the fold in 2010.

Figure 54: A Siemens designed mock-up of a future tube train, suggested another articulated design. The mock-up was unveiled in London on 8th October 2013. Photo: Kim Rennie.

Just a year after the demise of Tube Lines in 2011, a Siemens initiative revealed a new design for tube rolling stock with a concept they referred to as ‘EVO’ (short for evolution), to create interest in a new approach to tube car design (Figure 54). They offered a distinctively styled cab with a front end deliberately aligned to the LU roundel. They also expected to use a form of articulation to reduce the number of bogies under the train. To allow this within the small tube dimensions, a ‘tractor-trailer’ arrangement of car coupling was proposed, so that the bogies would not interfere with the walk-through area. Most cars would have only one bogie instead of two. This reduced weight but it would mean shorter cars.

Siemens worked on a novel concept to provide on-board air-conditioning and a solution to the problem of dispersing the heat generated by trains, an ever continuing challenge within the restricted tube tunnel profile. The proposed system envisaged train mounted tanks containing a “phase-changing polymer” (RGI, 2013) that would be cooled to below its freezing point while the train was running above ground, while on underground sections, the heat generated from the air-conditioning system would be used to melt the polymer again.

The new train was expected to produce less heat than existing stock, being 30% more energy-efficient and 20% lighter than other recent designs. Low-profile LED lighting was to be used to help maximise headroom. Other proposals included screens for advertising and a smart information system, to provide passengers at stations with real-time information on which parts of the next train were least busy.

Siemens offered a train that could be used under manual driving, automated operation with a driver in the cab, automated operation with no cab but with a member of staff on-board, or unattended automatic operation.

The train was designed to be adaptable if automation was to be brought in after the stock entered service. The wall separating the cab from the passenger area could be removed to create more passenger space.

Siemens hoped, in vain as it turned out, that invitations to tender for LU's Piccadilly Line fleet replacement would be issued in 2012. Orders for the Bakerloo, Central and Waterloo & City lines could take the total requirement to around 250 trains.

7.20 New Tube for London

The Siemens idea did not lead to a train order from LU but it did have a sequel in another design initiative originally known as the ‘Deep Tube Programme’ or DTP but it was rebranded as ‘New Tube for London’ (NTfL) early in 2013. The design eventually made public on 9th October 2014 (when the author was invited to attend) showed a strong affinity to the Siemens concept, not surprising since there is little that can be done to a metal tube tightly fitting within a metal tube. The devil is in the detail, which was carefully moulded by PriestmanGoode, the design company originally founded by Jane Priestman (who was once responsible for design on British Rail) and now run by her son, Paul (Figure 55).

Like the Siemens train, NTfL is designed for eventual unmanned automatic operation but will not run with it at first, if at all. It will feature a full driving cab but the units will be designed to allow the division between this and the passenger saloon to be removed in the future.

Overall, the cars are shorter than the current designs, with two, wider door openings per side and walk through access. In a repeat of a significant design error first seen on the 1967 Tube Stock for the Victoria line, there are no cab side doors. Access is from the passenger saloon. On the Victoria line, this led to problems where train crew changes taking place at Seven Sisters caused delays to trains because the driver was unable to reach the cab quickly as he had to struggle to pass through a crowd of standing passengers in the narrow aisle leading between the seats to the cab door. To resolve the problem, cab fronts were fitted with handrails and step plates to allow access from the platform across the front of the cab to the middle door. A similar arrangement had to be adopted on the Bakerloo line, which uses the similarly designed 1972 Tube Stock. The absence of cab doors may have to be re-thought if the new trains are to be introduced with drivers.

One area exercising the minds of designers is the motor and drive system. To get the low floor, wide gangway system, both the Space Train and Siemens designs showed that motors and wheels need to be smaller than the current designs. Smaller motors means that there would need to be more of them to match or improve upon existing performance and smaller wheels leads to thoughts about how they would perform through some of the very sharp curves and tight points and crossing installations on the older tube lines.

Figure 55: Beginning life as the 'Deep Tube Programme' (DPT) the 'New Tube for London' (NTfL) concept included a new train design as shown here. This owes something to both the original Space Train concept and the Siemens 'Inspiro' in terms of the look of the train but the treatment of the detailed design is, in the author's view, the best of the three. The detail work by the design house PriestmanGoode is well done. Photo: TfL.

7.21 Aspirations

The aspirations for the NTfL train include:

- No fixed on-board staff position;
- Forward facing cameras and obstacle detection at the front;
- Shorter, walk-through cars – 10 car bodies would replace an existing 7-car train;
- Articulation and walk through facilities;
- Fewer bogies and smaller wheels;
- An on-board 'power supply' to enable it to move forward in case of a traction current failure;
- Remote 'push out' capability;
- Interior air and humidity control;
- 10% less weight per m;
- Permanent magnet motors;
- Some trains equipped with built-in infrastructure monitoring systems.

It is clear that designing the new stock needed for the Underground will not be a simple task if all the aspirations are to be met. A complex series of interacting and interfacing engineering and operating issues on the trains are interwoven with equally complex infrastructure and control system requirements (TfL, 2014). This means that the desire to provide a frequent and reliable service for the passenger will only be achieved if a system engineering and integration approach is adopted at all levels. London Underground has, despite many attempts by policy makers to interfere from time to time, had a fairly successful record in this respect over the last 125 years, as the author has attempted to show in this research. And, the London Underground's heritage and reputation for innovation, tempered with the need for reliability, is still alive and well, as the new design proposals for the tube lines are showing us today.

7.22 Summary

From the author's research into the development of car body layouts, a clear pattern has emerged: That body design improvements were largely capacity driven. The passengers' traditional idea that 'everyone should get a seat', was quickly dispelled within days of Tube line openings in the early 20th Century. The interiors of cars were designed for maximum standing space, particularly near exits and passengers soon adopted the idea. As traffic grew, station stop management became important. If the number of trains required to carry the traffic offering was to be maintained, dwell times had to be reduced. This meant car design had to allow for rapid unloading and loading. Seats were sacrificed for entrances and exits and the relationship between door location and passenger flows became crucial.

Some experience in car layouts on urban railways had been imported from America but modifications to their designs included the introduction of centre doors and the enclosure of the open gated ends and, from circa 1912, remotely operated doors were trialled, followed by more door openings per car, longer cars and the sacrifice of more seats. On the tube cars, the low floor required wheels to penetrate the passenger space so seating had to be designed to suit and door positions became fixed. By 1930, tube car layout and door positions became fixed and they remain the same to this day (section 6.10 et seq.).

Up to the 1970s, the only radical improvement was the provision of four sets of double doors per car side for the Circle & Hammersmith line’s C Stock. This was easily done on the sub surface lines because of their larger structure gauge. But, by the 1970s, some of the drivers for better dwell times were lost as traffic levels fell, and this resulted in the reduced door openings provided on the D Stock. Now, after 20 years of continually rising traffic levels since the recovery of the mid-1980s and expectations of further growth (TfL, 2014), dwell time management and its relationship with train door design is more important than ever and this must continue to drive improvements.

The next phase of car body design, represented by the New Tube for London, attempts to break out of the 1930s body configuration dependency by introducing articulation and wide, open walkways between tube cars. It also aspires to all double doorways spaced evenly through the train length. In the author's view however, the currently planned absence of side cab doors does not align with the idea that the new trains will start operating with drivers (Section 7.19) before conversion to unattended automatic operation. This last issue presents a clear example of how corporate memory loss can affect the future performance of a railway system and that some means of retaining it is essential.

7.23 Conclusions

This chapter has demonstrated that bringing a new system into passenger service without an adequate trial period or a prototype is bound to lead to trouble. The District Railway’s new fleet of trains introduced in 1905 with powered doors proved unreliable and even dangerous and had to be withdrawn within three years. The LER’s introduction of powered doors in 1920 was more considered and they introduced the new system with a prototype train but it showed problems with the door recycling system and this feature had to be quickly withdrawn. Although a prototype was used then, even by 2009, the lesson had not been learned and an expensive and untried “sensitive edge” was installed on the whole fleet of 2009 Tube Stock. Over the years since, the author has been involved in some of the various attempts that have been made to get better reliability but they have not proved to be a success.

This chapter also shows that it is wise to moderate radicalisation with prototyping. The idea of “evolution not revolution” should not be lost. In particular, the proposals for New Tube for London (NTfL), incorporating many new and largely untried systems, arguably present a very high risk for a planned production run of 250 trains. From his experience, the author would propose that there should be at least two prototype trains tried out in passenger service.

The importance of reliable and adequate door service is another lesson to be learned. As an example, the decision to reduce the D Stock door width in order to save on equipment and reduce weight was to prove a serious drawback whenever there was a higher than normal level of traffic. A similar design was also provided on the 1983 Tube Stock and this led to its early demise, long before it was life expired. Here, it was forgotten that a train is a high investment commitment and has a long life and therefore must be designed to cope with a wide range of traffic levels. These lessons should not be lost.

8 Bogie Design

8.1 Introduction

The interface between the railway wheel and the track that guides it is a crucial part of the railway system. If a vehicle is to present anything close to a satisfactory ride for its passengers, the arrangement of the suspension and the bogie that acts as the interface between the car body and the wheels. This chapter looks at the development of the bogie on the London Underground as used for electric traction and seeks to show the somewhat difficult progress towards a comfortable and sustainable bogie design. From this development story, a number of lessons have been learnt. Some others, the author fears, may not have been learnt.

8.2 US Bogies

Perhaps the easiest way to understand bogie design development on the Underground is to look to the US, where the railway bogie was invented in 1831 by John B. Jervis (Shinn et al, 1885) and where a simple version was developed which is now called the 3-piece bogie (Figure 56). The US-designed bogies that appeared on the Underground at the turn of the twentieth century showed their origins in the features of the 3-piece design.

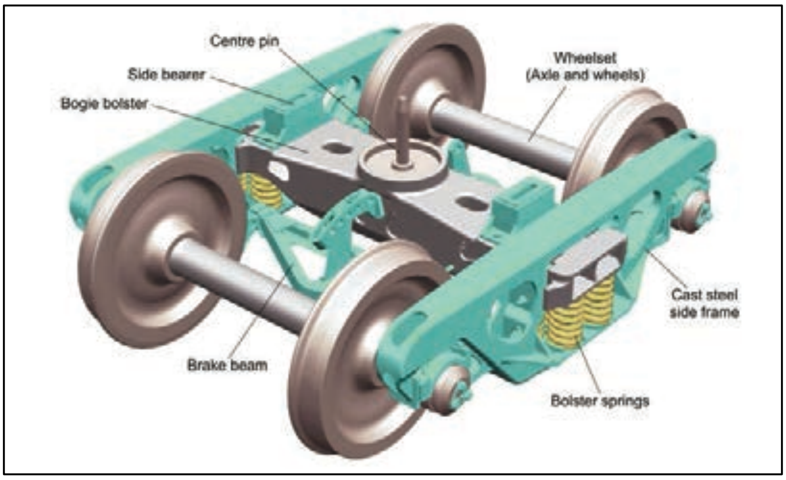


Figure 56: Drawing of US 3-piece freight car bogie that was the foundation for the American designs used on the early London Underground electric stock. This diagram is useful to see the main parts of a bogie. The bolster sat on top of the bolster springs and carried the car body on the two side bearers. Thus, the whole weight of the car body was carried by four sets of bolster springs. The centre pin acted to retain the bogie and body in alignment and allowed the bogie to turn to follow curves in the track. In this design, the wheelsets were not equipped with springs. On passenger bogies, each wheelset axle has springs at each end. Collection: Author.

The 3-piece bogie became almost universal in North America for freight cars. It did not provide a wonderful ride and better versions were developed for passenger cars but the freight version has survived to the present day and versions of it are used in

Britain on some freight vehicles. Along with this design, more sophisticated bogies have been developed for passenger cars.

It should be mentioned here that the Americans always referred to bogies as ‘trucks’, and still do. The Underground, who had adopted the American word ‘car’ instead of the British ‘coach’ or ‘carriage’, also called bogies trucks and the author recalls that the Underground’s vehicle overhaul works at Acton still had its ‘truck shop’ until it was closed in the late 1980s.

8.3 The Equaliser Bar Bogie

The next stage of bogie development in the US was the equaliser bar bogie. This was developed for passenger vehicles in the 1860s (White, 1978, p. 500) and eventually became standardised by the Master Car Builders (MCB) association (now the Association of American Railroads or AAR) in America as the ‘ideal’ bogie design (Hitt, 1911, p.37). It first appeared in Britain under Pullman cars introduced on the Midland Railway in 1874 (Jenkinson, 1996, p. 208). It never really found favour here but versions of it were used on various Underground lines in the early years of electrification (Figure 57) and a more mature version appeared under British Railways coaches in the late 1950s and early 1960s as the ‘Commonwealth’ bogie.

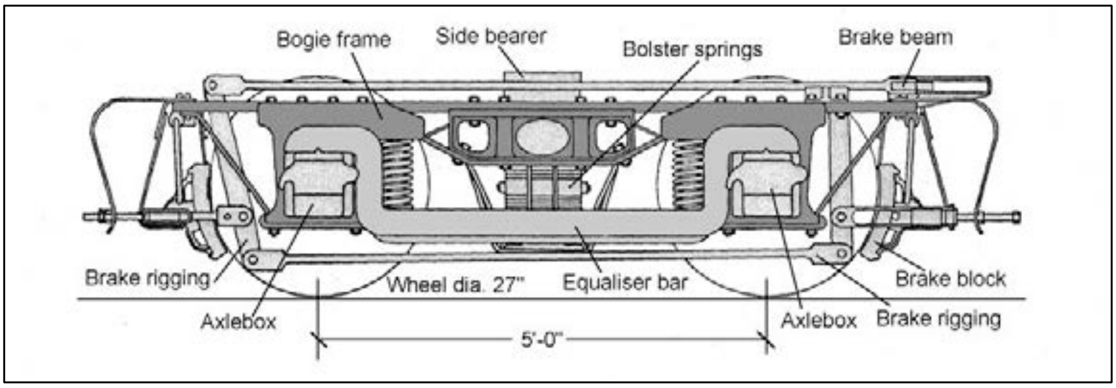


Figure 57: A District Railway trailer bogie, known as Type K, as built for the new 1905 B Stock for electrification. This was an example of the equaliser bar type. The bar (shown in light grey) connected the two axleboxes on each side on the bogie. The bogie frame sat on two coil springs mounted on the bar. The effect was to try to equalise movement between front and rear wheelsets and thus minimise the effect of wheelset movement on the bogie frame. The bogie also had a swing bolster. Drawing: Adapted by the Author from an original by the late Stuart Harris.

The equaliser bar bogie was a much more sophisticated design than the 3-piece bogie and it incorporated two new developments – the swing bolster and equalised primary suspension. On the original 3-piece bogie, the bolster was just one piece but the swing bolster arrangement had four main parts – a set of four swing links, a spring plank, a pair of springs and the bolster itself (Figure 58). The spring plank was hung from the transoms by steel rods or ‘swing links’ which allowed it to move from side to side within the space between the side frames. The plate was thus able to float or swing – therefore ‘swing bolster’. The clearance at the ends was quite small – about 2 inches or 50mm so there was a limit to the movement but it was sufficient to reduce the effects of the sideways movement of the bogie, an effect known as ‘hunting’. The spring plank (it was originally wooden, hence the ‘plank’ in the name, which has stuck to this day) carried the springs. Then the bolster (which was also wooden in some early examples) sat on top of the springs and the car body sat on top of the whole assembly.

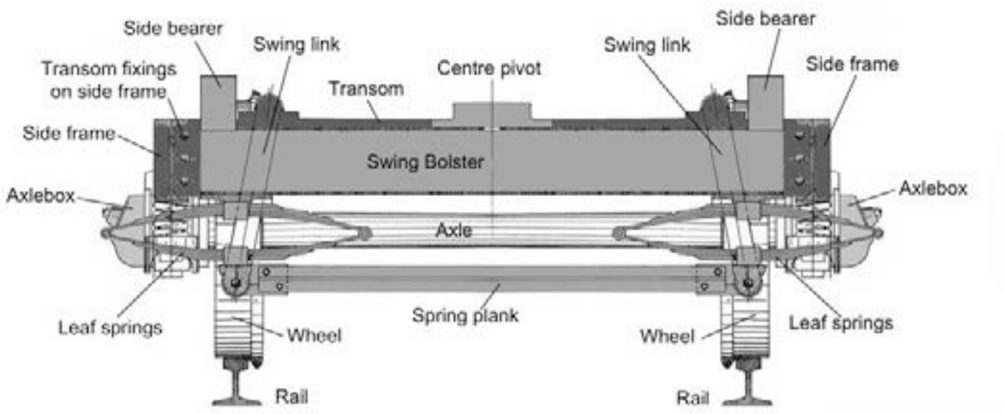


Figure 58: This drawing shows a cross section of a bogie with a ‘swing bolster’ suspension system. The swing bolster consists of four main elements: The bolster, two sets of leaf springs, the spring plank and two sets of swing links. The bolster sits on top of the springs (leaf springs in this design), the leaf springs sit on the spring plank, which is suspended from two pairs of swing links. The swing links hang down from fixings on the bogie transoms - the two cross members (only one is shown here) that are fixed to the bogie side frames. When the car body is lowered on to the bogie, it rests on the two side bearers fitted on top of the bolster and is located by a pin that fits into the centre pivot. Drawing: Modified by Author from original drawing of early American bogie.

Both the District and Central London adopted the equaliser bar bogie but in different guises. The District used it at the trailing positions on its 1905 B Stock (Figure 57) while the Central London used it as a motor bogie on the 1903 motor cars (Street Railway Journal, 1902, p. 604). The design had two sets of springs. The equaliser bar suspension used both coil and laminated springs. They were often used in combination. Coil springs tend to be bouncy whilst laminated springs are more sluggish in response. The combination of the two on a bogie work in opposition to each other and they provided a means of softening the ride whilst maintaining stability.

Going back to the swing bolster setup, we should note that it was not unique to the equaliser bar bogie (Figure 58). It was adopted by most bogie designers both in Britain and US. It remained popular until the 1960s when the first examples of solid bolsters and air springs began to appear here. The equaliser bar design was always a US favourite but it made little impact here, largely because it was considered too heavy. Its main use on the Underground was on the District, the Waterloo & City and the Central London Railway. The ones on the District had cast steel side frames, with the rest of the structure pre-fabricated and assembled with bolts and locknuts. They did not wear very well on the District's poor track and they were gradually replaced by a traditional British design. The Central London design lasted the life of the stock and then survived until the 1980s, when the author saw them under the tube stock electric sleet locomotives.

8.4 Hedley's Bogie

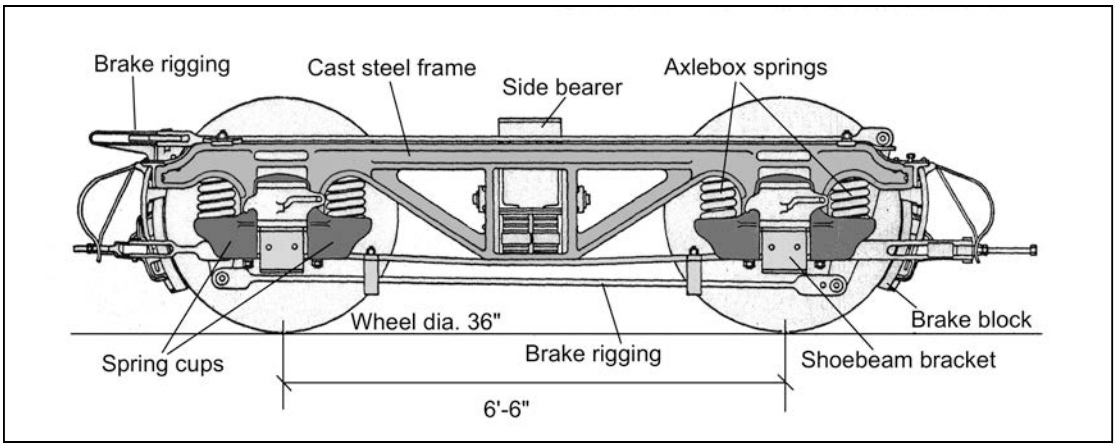


Figure 59: The District and UERL tube lines used a common motor bogie with a cast steel frame designed by Frank Hedley of Chicago and New York. The frame sat on coil springs placed in 'spring cups' fitted to the axleboxes. The standard spring bolster provided the secondary suspension. The design was not successful on the District and bogies had to be replaced on many cars over the years but it did last on the tube lines. There is much evidence to suggest that the poor quality of the District's track had a lot to do with their bogie problems. Drawing: Adapted by the Author from an original by the late Stuart Harris.

Another US bogie to see service on the Underground was the 1905 District and LER motor bogie originally designed for use in Chicago by Frank Hedley (Carlson & Keevil, 1976, p. 189). Hedley was one of Charles Yerkes engineers who came to London for a short time to assist with the electrification of the District. He had designed bogies for both the South Side and North Western elevated lines in Chicago and then went on to become General Superintendent of the Interborough Rapid Transit (IRT) subway in New York City. His designs had the standard swing bolster arrangement but were quite different from the equaliser bar design in having individual axlebox suspension and one-piece cast steel side frames.

The Underground's bogie (Figure 59) had a new feature was that the axleboxes had extension wings to their castings which formed 'spring cups' on either side. These carried coils springs upon which the main bogie frame rested, also using spring cups. The two axleboxes on a side were connected by a steel strap, fixed to their bases, which acted as a stiffener.

The 1905 Hedley design was used as the motor bogie for all the original London Electric Railway (LER) Gate Stock and the District's B Stock. Almost 400 of them were built. The design originated in Chicago and later versions of it appeared in New York City when Hedley moved there. The main side frame appears to have been made up of a single cast steel piece which rested on the axlebox springs. The casting comprised diagonal and vertical members acting as stiffeners to the main longitudinal piece so it offered a completely different visual impact compared with the 1903 version. In fact, from the side, it vaguely resembled the 3-piece freight bogie.

The bogie, designated type A by the District, gave problems (MDR, 1911). Cracked frames were the most common. One suspects this was partly due to quality control but it would seem that the condition of the District's track defeated both the US designed bogies which were tried on it and both were eventually replaced with British designs. A cast steel frame presents a more rigid structure than say, a riveted frame, so it would be more prone to fractures. Its one advantage is that it is generally cheaper to produce than the typical British design requiring riveting (Graff-Baker, 1952, p. 320).

8.5 British Bogies

The basic difference between the traditional British bogie and the American 'truck' was that the British used steel plate or pressed steel sections instead of the cast steel frames preferred in the US. The pressed steel was formed into wide but shallow channel sections to give strength and pieces were riveted together to form the frame.

On the Underground, the Metropolitan Railway was, as far as bogies were concerned, British to the core. They stuck to the traditional design which was standard on almost all GB railways (Figure 60). They used the pressed steel format for all the stock built from 1904 until a plate frame version appeared under the 1925 motor cars and subsequent vehicles (Snowden, 2001).

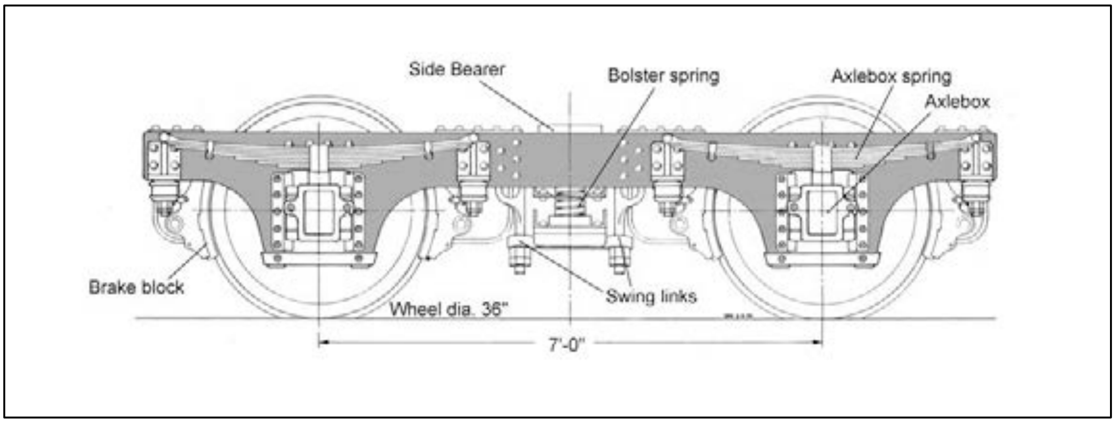


Figure 60: Standard Metropolitan Railway plate-frame trailer bogie (later referred to as Type MR) with laminated (leaf) primary springs and coil bolster springs. The leaf springs rest on top of the axleboxes and are fixed to the side frame with brackets attached to 'spring hangers'. These spring hangers have to allow for spring movement at the connections so they are usually hooked over the spring ends. At the bracket end, it is usual to have an additional small 'hanger bracket' spring, which can be a steel coil or rubber. The usual sprung bolster is provided but with coil springs. A similar but heavier design was used for motor bogies. The brake rigging is not included on this drawing, originally by J. Snowdon (2001) and adapted by the Author.

Once the District discovered that the new-fangled American bogies could not hack it on their track, they too resorted to the traditional British design. All the bogies produced for the District from 1910 onwards conformed to this pattern until the appearance of the welded designs of the late 1930s. The LER also adopted British style bogies for all cars built after the original Gate Stock of 1905-7. Only the Central London went American for a second time when they ordered MCB bogies for the 1915 Ealing Stock but these were soon replaced by plate-frame bogies when the duty cycle on the Bakerloo service to Watford proved too much for them.

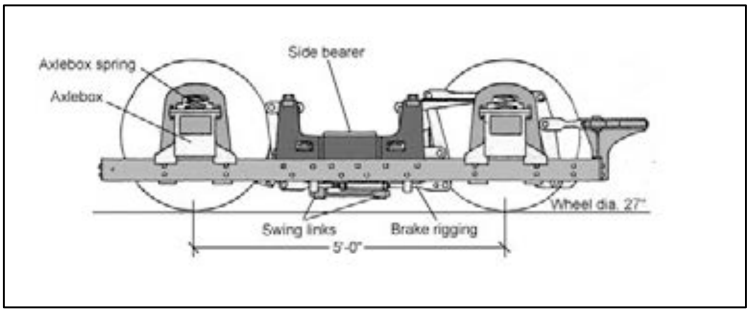


Figure 61: Trailer bogie used under the LER stocks originally built for the Bakerloo, Hampstead and Piccadilly lines in 1906-7. The design seems very flimsy but it lasted the 25-year life of the stock in passenger service and survived another 20 years under some cars used as engineer's vehicles. It must have given quite a harsh ride with such small springs. Note the large castings (in dark grey) added to carry the brake hangars. There seems to have been some sort of swing bolster but it was in a very tight space. Drawing: Adapted by the Author from an original by the late Stuart Harris.

8.6 Tube Trailer Bogies

Because of the very restricted space under tube cars, their trailer bogies were compact, to say the least. The original LER Gate Stock bogies had a low slung frame but it was a much lighter affair than the designs used for later stocks. There is little information about it but photos and drawings show that the frame rested on small coil springs mounted on top of the axleboxes (Figure 61). Also, it seems to have been pre-fabricated from steel parts. Similar versions of it can be seen under the Cammell Laird trailers of 1920 but the 1914 built cars for the Bakerloo used plate-framed bogies. There are no obvious reasons for this inconsistency.

By the mid 1920s tube car bogies had miniaturised plate frames designed to fit under the car floors (Figure 62). The shape of the side frame reflected this restriction. It was dropped low in relation to the axles and the outline at the top followed the wheel's shape so it could fit into the opening in the car floor. Motor bogies (Figure 63) were larger and heavier and some were of such robust design that they have lasted to the present day under battery locomotives.

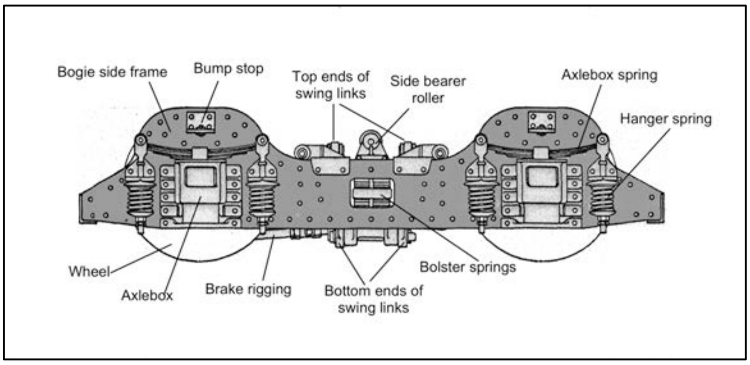


Figure 62: 1927 tube trailer bogie known as the W2 Type used under many Standard Tube Stock cars. It had a 5ft wheelbase and 27inch wheels. The design was based on traditional British principles with a riveted frame but it had leaf springs for both primary and secondary suspension in an attempt to restrict movement within the confined space. The frame was also specially shaped to fit within the low height tube car underframe. Drawing: Adapted by the Author from an original by the late Stuart Harris.

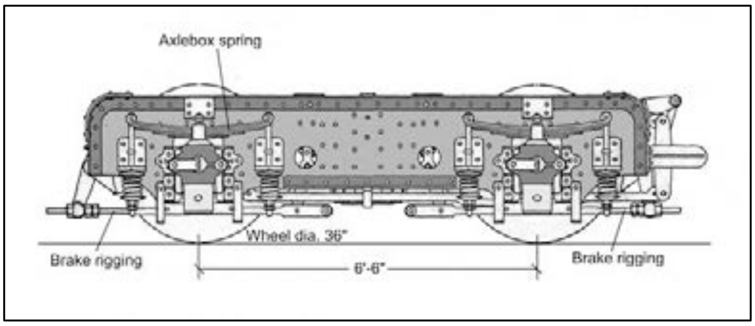


Figure 63: The final design of Standard Tube Stock motor bogie. A heavy plate framed design that lasted for many years after the stock was scrapped. It is still in use under some of the Underground's battery locomotives. Drawing: Adapted by the Author from an original by the late Stuart Harris.

8.7 Welded Frames

By the mid-1930s, bogie design had settled down to the standard British pattern of plate-framed or pressed steel frames, which were broadly in line with the main line pattern on the sub surface lines, and to the more compact design required on the tube lines. The frames of these bogies were all riveted but riveting is labour intensive, requiring a large number of holes to be accurately drilled for the rivets followed by the fitting of the rivets. Rivets work loose after time and, because of this, much re-work was necessary during the maintenance cycles.

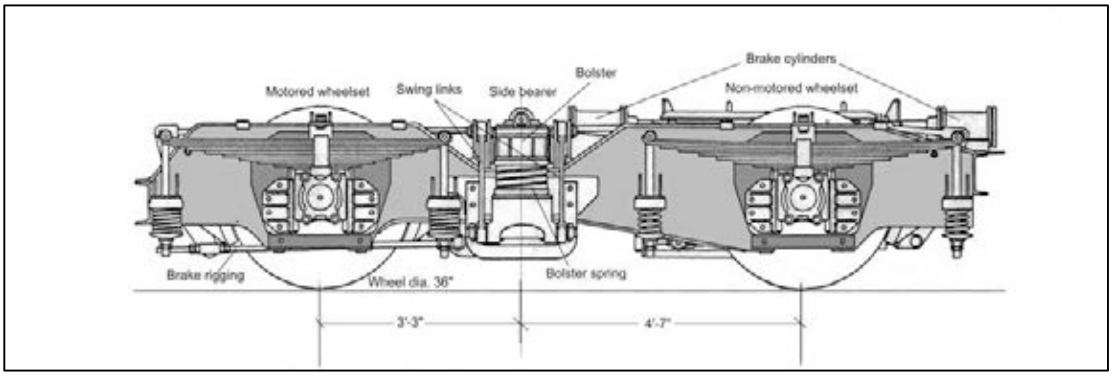


Figure 64: Side view of P & Q38 Stock bogie showing the frame (in grey) and various parts. These include the external swing links and the steel coil bolster springs which sit on the spring plank and carry the bolster itself. The bolster spring is clearly visible outside the side frame. On most designs, it was inside the frame and very difficult to see. The end of the bolster can be seen on top of the spring, just below the side bearer roller. Below the spring, the end of the spring plank can be seen, hanging from the ends of the swing links. The unusual feature of this design was the externally mounted bolster spring. The intention was to widen the bolster and so reduce the rocking motion of the body. Also, to improve traction, the motored axle was closer to the centre of the bogie than the trailing axle, hence the asymmetrical wheelbase. Drawing: Adapted by the Author from an original by the late Stuart Harris.

The Underground's chief design engineer, W.S. Graff-Baker (1952), wanted to improve the design and performance of bogies and he looked to welding as one possible answer. He developed welded bogie designs, which were provided under the 1936/38 Tube Stock and the new surface stocks of the era - the O, P and Q38 Stocks. There is no evidence that any pre-service experiments were carried out so it seems that, in typical fashion, Graff-Baker went ahead with his proposals and imposed them on two large new fleets of rolling stock.

Unlike most of Graff-Baker's other innovations, his welded bogies were not a long-term success. The treatment they got from the rough track on the Underground led to cracked joints and fractured frames and a constant cycle of repairs was always on the go. After World War II, riveted frames re-appeared under new trains and remained as the norm for another 30 years. In spite of this, the welded design was an interesting venture and it also had a novel feature in the design of the bolster, which extended outside the side frame alignment in an attempt to improve the stability of the vehicle. The surface stock version of this design is shown in Figure 64.

8.8 Welded Bogie Features

The bogie is welded where necessary to keep the parts together. Only the horn guides are riveted because these had to be removed periodically for relining. Behind them, the outline of the strengthening plates added to the bogie frame can be seen (Figure 64). More strengthening was added in the area behind the bolster spring because the depth of the side frame was reduced to allow the bolster to pass over the top of it; an obvious source of weakness. This was avoided on the tube version of the bogie because, although the bolster and its springs were longer than normal, they were contained inside the side frame. This was made possible by angling the frame into a 'bay window' shape around the bolster ends (Figure 65). The author was most familiar with this design.

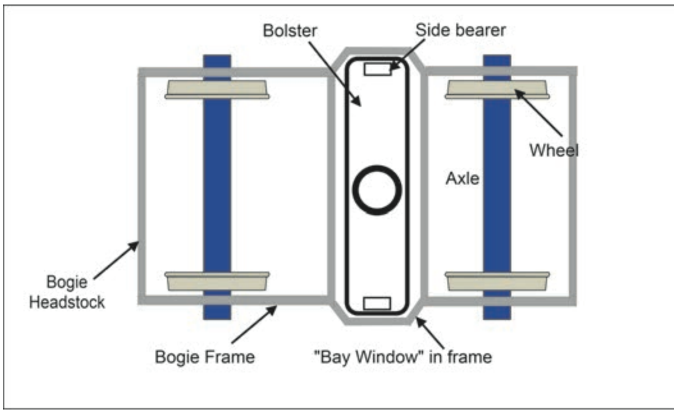


Figure 65: Schematic of plan of 1938 Tube Stock bogie showing the extended bolster and 'bay window' in the side frame to accommodate it. The idea was to widen the bolster so as to improve the platform upon which the car body sat. It did provide a rather soft ride, certainly better than earlier trains. What proved troublesome for the bogie was the welded construction. Drawing: Author.

Two more new features that appeared on these bogies were the asymmetrical axle positioning and the bogie mounted brake cylinders. The bogie had only one traction motor and its axle was positioned so that it was nearer to the bogie centre than the trailing axle was, rather like the 'maximum traction' bogie adopted on some tramcars. This arrangement increased the weight on the axle and gave better adhesion. The distances from the bogie centre line of the surface stock version were 3ft 3ins for the motored axle and 4ft 7ins for the trailing axle. Up to this time, motor bogies had always had two motors, one on each axle. For the next 30 years, all new designs had one motor per bogie and the same design of bogie under both motor and trailer cars – it standardised the bogie design and lent itself to conversion of trailer bogies to motor bogies, as Graff-Baker intended would be done when the traction current power supplies were upgraded to allow all-motor car trains.

The other new feature was the bogie-mounted brake cylinders. Up to the mid-1930s, there was only one brake cylinder per car. The movement of the piston was transmitted to the brake blocks at the wheels by a complex system of rods and levers called brake rigging. The rigging was supposed to ensure that, when the piston moved to apply the brakes, all the blocks hit the wheel treads simultaneously and with the same pressure. Getting this to happen with any degree of consistency required a careful design of the rigging and then consistent and accurate maintenance and adjustment on a regular basis. The complexity of the brake rigging meant that each train had a huge number of links and pins, each with their own bushes and split pins. Keeping the railway supplied with these created its own cottage industry at Acton Works, which supplied depots with parts.

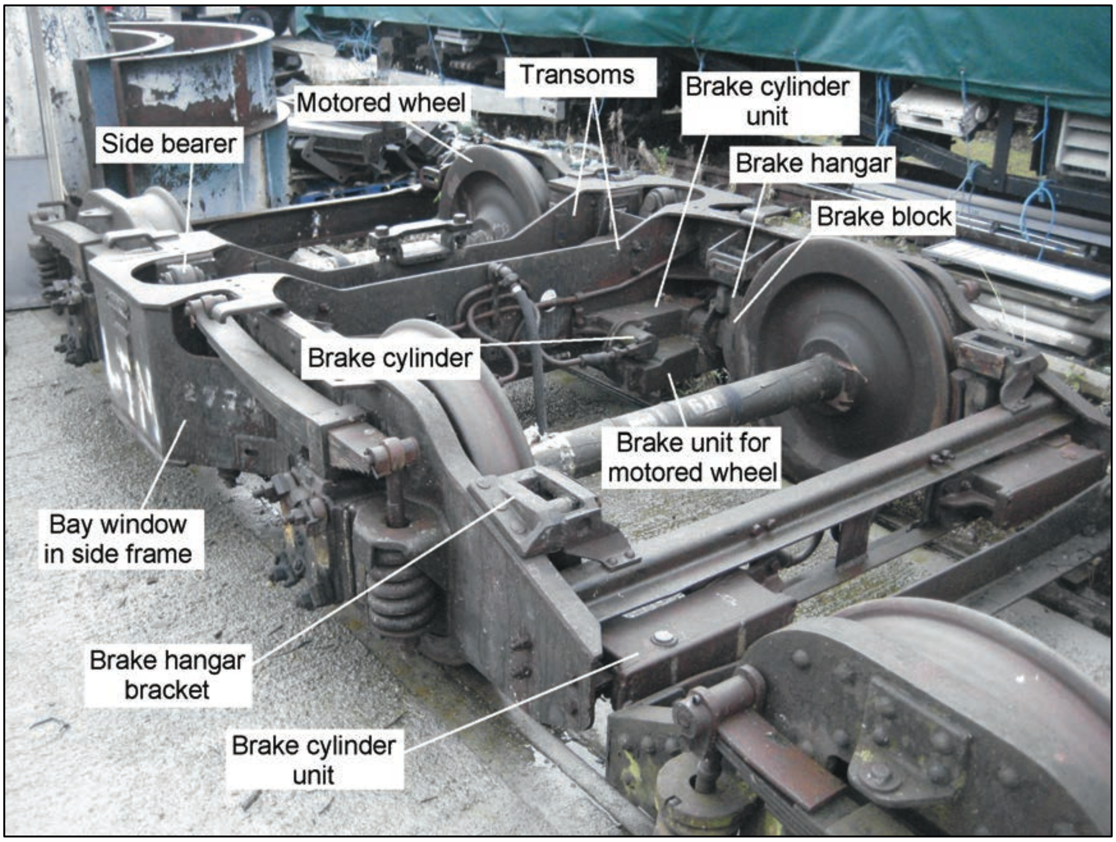


Figure 66: A 1938 Tube Stock bogie in store at the LT Museum. It shows the brake cylinder units and how they are fitted into the cramped frame of the bogie. Each wheel has two brake blocks, one on each side. Each block has its own brake cylinder unit, consisting of an air cylinder, operating lever, return spring and slack adjuster. Because the space around the motored axle is tight, the brake cylinder unit for the inside brake blocks is mounted on the trailer side of the bogie bolster. Note also the 'bay window' shape for the side frame, which gives space for an extended bolster with side bearers located further apart to aid car stability. Photo: Author.

Graff-Baker (1952, p. 323) was well aware of the problems with brake rigging. He wanted to find a way of getting rid of it but this meant taking the cylinder closer to the block and the wheel. There is little room to do this on a conventional bogie and even less on a tube bogie. Nevertheless, he managed it. He did it by making the brake cylinders smaller and fitting them to the bogie frame. This got rid of the long links between the cylinder and the bogies. His first attempt on the surface stock produced a design with two cylinders on each bogie. This reduced rigging to a per bogie basis. The later version on the tube stock got 8 cylinders under each bogie and completely eliminated rigging. He did it by mounting each cylinder in a casting which included the operating lever and slack adjuster. The casting was bolted to the bogie frame. It was small enough to squeeze between the brake hanger, which held the block, and the headstock (or transom). It solved the rigging problem but it required careful manufacture to ensure there was enough room between the hanger and the wheel to fit a new block. When new, the 1973 and D Stocks both suffered from badly made and mounted brake components which made the fitting of new blocks impossible in some locations. Some of us unfortunates spent a lot of time running around looking for part worn blocks to replace fully worn blocks in places where new blocks would not fit.

For the surface stock, the 1947 version of the bogie fitted to the new R Stock had 8 cylinders per bogie. This made re-blocking easier as one did not have to go through the rigging adjustment that was still required on the 1937-8 versions of the bogie. When an R Stock came in for re-blocking, the car examiner would look along the side of the train so see which were R38 vehicles and which were R47 or R49s so they could judge what work was involved. One always hoped to see no R38s.

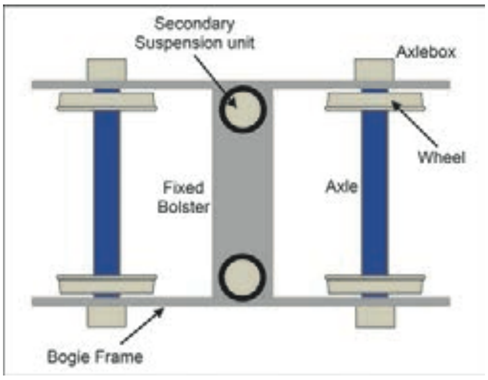


Figure 67: A schematic of a welded, box frame bogie with a fixed bolster forming an H shape. There were no headstocks and no transoms. The secondary suspension sat on top of the bolster ends. This was normally air bags of solid rubber blobs. The design first appeared on the D Stock, using rubber blobs. Drawing: Author.

8.9 To Weld or not to Weld?

The problem with a welded bogie is that the stresses occurring in the steel during welding can quickly cause fractures in service. This means that the whole frame has to be heat treaded to 'de-stress' it. Even with this treatment, Graff-Baker's welded frames proved too rigid for working over the sometimes very poor Underground track and cracked frames and failed welds were common. Maintenance expenditure on bogies was still very high. In the end, the problems forced the revision of policy the author mentioned earlier and the joints between side frames, headstocks and transoms of bogies built after World War II went back to rivets so that the de-stressing could be avoided and some flexibility was restored to the frame under bad track conditions. Welding was retained only for brackets or strengthening elements such as the side frames where stiffeners were welded to the top and bottom of the side plates.

As with much of history, fashions change and welding, as a fashion, has gone in and out of favour and is now back in. It first re-appeared in the original D78 Stock bogies, which appeared on the District line in 1980 and which the author helped bring into service. They were designed with welded, box section side frames and a welded bolster to form a solid H shape. It was very simple. There were no headstocks and no transoms. Both primary and secondary suspension was solid rubber. The secondary suspension was described as 'diablo', for some reason which escapes the author, since each spring looked like a pair of Christmas puddings placed one above the other, top to top. Unfortunately, the bogies were poorly made and the design was most unsuitable for London Underground conditions. Fractures began to appear and the bogie was so stiff that, under the extreme track conditions, like those that existed at Whitechapel before it was rebuilt in 2012, where a combination of difficult vertical and horizontal curves occur in complex point and crossing work, the bogie sometimes derailed. Severe speed limits were imposed in places and eventually the fleet was given new bogies as described below.

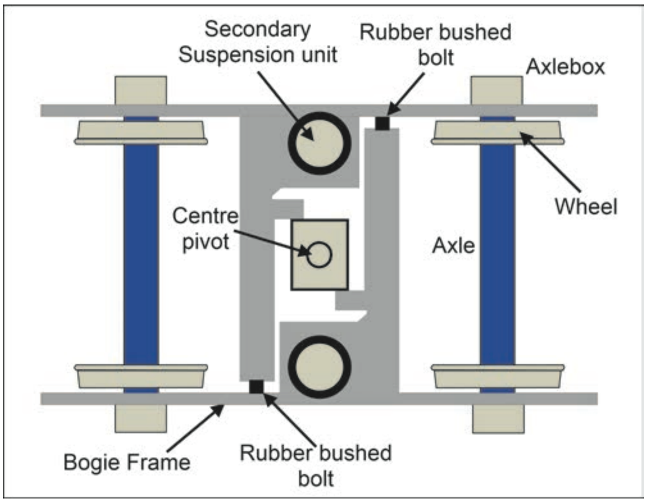


Figure 68: A schematic of the flexible frame bogie built by Adtranz (now Bombardier) for the 1995 Tube Stock and then used to replace the original bogies under the D Stock and for the 2009 and S Stocks. The design provides two 'T'-shaped main frames coupled together by flexible bolts and linked to the car body through a centre pivot coupled to each piece. Drawing: Author.

The author recalls that the 1992 Stock also had a welded H frame bogie, supplied by Kawasaki but it was rather different from the D Stock version and it also had air bag suspension. It too was not a successful design and was replaced by a new design from

Siemens in 2010-11. Alstom built their own design of H frame bogies for the '96 Stock but they fitted them with rubber 'Christmas pudding' suspension blobs instead of air bags.

In a curious alliance between two rivals (well, curious to the author at least, since he worked for one of them for a time and the other one was regarded as serious competition), Alstom decided to use bogies designed by Adtranz when they offered the 1995 Tube Stock to London Underground. These were specifically designed to cope with indifferent track and to avoid the sort of derailment problems suffered by the D Stock. They are designated 'flexible-frame'. This is because the bolster is split transversely so that the bogie is actually in two halves. They are connected by rubber damped links (Figure 68). This allows the two sides some independent movement and can partly compensate for the undulations of the track. The design has been a success and a modified version was chosen to replace the D Stock bogies, as mentioned above. The replacement bogies were fitted between July 2000 and May 2002. A similar design is used under the new S Stock and the Victoria Line's 2009 Tube Stock.

8.10 Rubber Suspension

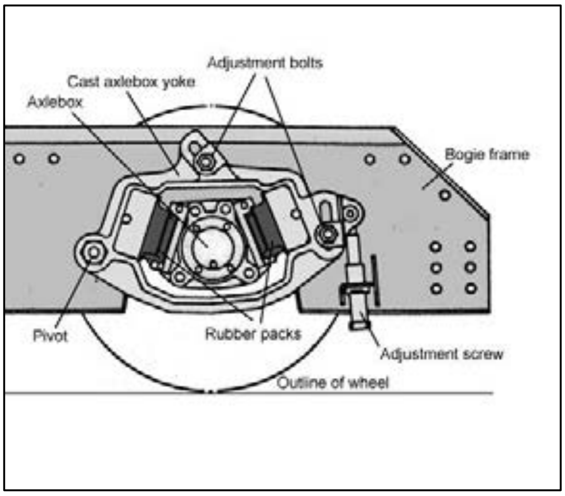


Figure 69: Metropolitan line A Stock axlebox suspension unit showing the angled rubber packs used as the primary suspension. The packs were set inside a specially designed yoke. The position of the yoke could be adjusted for wheel wear. The design was used on most tube and surface stock built between 1956 and 1973. Drawing: Redrawn by Author from an original by the late Stuart Harris.

Steel suspension involves a lot of mechanical interfaces. Brackets carrying spring hangers, axleboxes sliding in horn guides, knife edge or bushed bearings for swing links, interfaces between springs and plates and the tendency of all these to wear or fracture in time. Reducing these or even getting rid of them altogether was a much sought after objective. Graff-Baker saw rubber as the solution (1952, p. 337). It was sometimes used for spring hangers in earlier times but it first appeared on the Underground as the main suspension system in an experiment on a bogie fitted under a 1938 Tube Stock car in 1952. This was considered a success and it was forthwith adopted as the new standard for the aluminium-bodied trains built from 1956 onwards. It went into production on the 1959/62 Tube Stocks and the A Stock. From that time, the Underground never went back to steel suspension.

The rubber suspension consists of packs of rubber and steel made into a chevron-shaped sandwich. A pack is then fitted on either side of the axlebox at an angle to allow some vertical and horizontal movement. The whole unit is contained inside a yoke attached to the side frame by a pin at one side and two adjustable bolts, one on the other side and one on top. (Figure 69). When it first appeared on the 1956 Tube Stock, the rubber pack design was much heralded by the manufacturers Dunlop under the name ‘Metalastik’. The Dunlop company’s Metalastik division has since been acquired by the Swedish company, Trelleborg Industrial AVS.

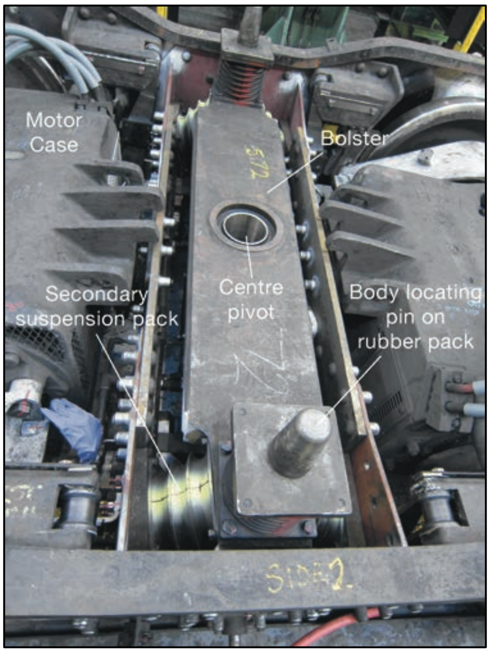


Figure 70: This photo shows the bogie bolster for a 1972 Tube Stock motor bogie. It is mounted on four secondary suspension packs, fitted at angles at each corner of the bolster. A centre pivot is provided to locate the rotational point for the bogie while two locating pins for the car body are mounted at each end of the bolster. Note that the bogie transoms are pre-fabricated steel plates and it appears that they have recently been replaced. The 1972 Stock is the oldest passenger stock on the Underground and it is likely to have to last another 12-15 years before replacement. Photo by author.

The rubber packs were also applied to the bolster suspension. Instead of sitting on a plank hung from swing links, the bolster was mounted between the transoms and rested on the rubber packs (Figure 70). It was shaped at the ends so it could rest on the packs, which were squeezed in at an angle between the transoms. The characteristic of the rubber was such that several shock absorbers had to be fitted between the bolster and body to soften the frequency of the vibration. The tendency of rubber to bounce at high frequency is a price which has to be paid for the lower maintenance requirements compared with steel suspension.

Figure 71: A 7-car train of 1959 Tube Stock at Woodside Park in the late 1970s. A large fleet of these and very similar 1962 Tube Stocks were built for the Central and Piccadilly lines. This was the first production stock built with rubber suspension. The '59 Stock began moving to the Northern to replace 1938 Tube Stock when the Piccadilly line began getting new 1973 Tube Stock. Photo: B.R. Hardy.

8.11 Air Suspension

At various times during the 20th century, the Underground has tried to overcome the problem of the enormous changes of car weight which occur during the normal service day. The difference between an empty car at 5 o'clock in the morning and a crush-loaded[10] car at 8 o'clock in the morning can be over 50%. This affects adhesion, even on dry rails, and if different vehicles in the same train have different loads and therefore different weights, it makes braking without skidding the wheels on the lightly loaded vehicles quite difficult. One solution lay in the idea of weighing each car and adjusting the braking accordingly. This is known as 'load weighing'.

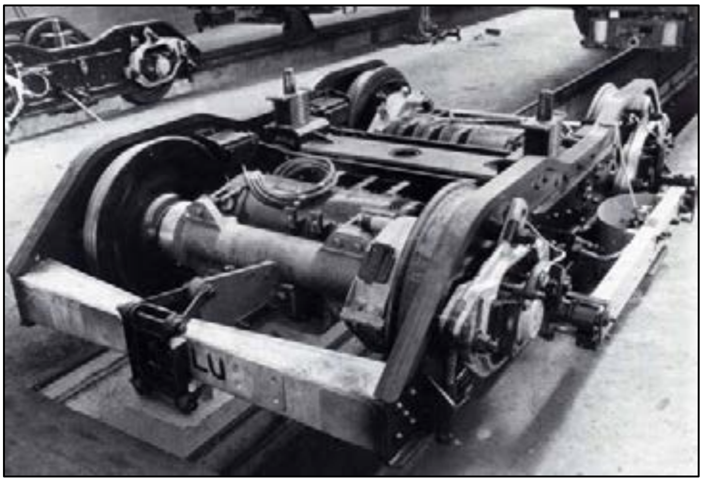


Figure 72: 1973 Tube Stock motor bogie. The design is typical of the 1960s-70s. The side frames were of steel and the headstocks of aluminium. Rubber packs are used for the suspension. Note the negative shoe is carried by the board seen fitted between the headstock and the motor suspension tube. Photo: Author's Collection.

[10] "Crush loaded" is a technical term used to mean packed to capacity. If you feel crushed sometimes in the rush hour, this is about half what the real "crush loaded" term refers to in terms of numbers of passengers. It is rarely reached in practice.

8.12 Load Weighing

Load-weighing of cars, as an idea, has been around for many years. Graff-Baker tried it experimentally in the early 1930s on a Standard Stock car but it proved too difficult within the constraints of the day and it was not until the late 1960s that the idea resurfaced. The author recalls an experiment was tried on an A Stock vehicle (No. 5218) using air bags in place of the secondary (bolster) suspension. A rubber bag was filled with compressed air fed from the train's main air supply system. The pressure was set to a level for tare weight (empty) and then increased as the car was loaded. This was done with a link rod fitted between the car body and the bogie frame that detected the change in weight and, using a valve connected to the rod, adjusted the pressure inside the bag to suit. A fall-back rubber spring was provided as a support in the middle of the bag in case it burst. The signals generated by load weighing were used to adjust acceleration and braking.

The new suspension system was fitted to the C Stock as built. The air bag was described as the 'Metacone' (Bruce, 1983, p. 116). A measuring link was provided on each bogie and a combination of the output from the two was transmitted to the traction control and braking systems on the car to adjust them accordingly. The idea was wonderful but by the time the C Stock was refurbished in 1992-5, the Metacone air bags were worn out and the pneumatic control valves were becoming a maintenance liability. The system was removed and replaced by 'diablo' (Christmas pudding shaped) rubber blobs like those on the D Stock.

Air suspension suffered a setback as a result of the C Stock problems but, one could fairly say that it suffered perhaps because it was a pioneer design and little was known about the effects of the hammering it was to get from the Underground's track and the very harsh duty cycle of the Circle Line service. It reappeared almost 30 years after this first design in a more robust form under the 1992 Tube Stock. However, there seem to have been uncertainties about its use in service on the Central Line, perhaps more to do with the bogies than the air suspension, and Alstom did not supply it for their bogies under the Jubilee Line's 1996 Tube Stock. It finally returned with the Adtranz flexible frame bogies on the 1995 Tube Stock and the 2009 and S Stocks.

The re-introduction of air suspension brought another problem into the spotlight again - stepping distances on and off trains. In order to accommodate the air suspension on the '95TS, the floors are noticeably higher than the 1959 Tube Stock it replaced, much to LU's disgust. This increased the stepping distance. Apart from any safety considerations, the greater the stepping distance, the slower the boarding and alighting times. On LU's new Bombardier built stocks, which has very similar bogies, the wheels are smaller (700mm instead of 770) so that the floor is lower, even with air suspension (Neil, 2016).

8.13 Bogies Under Articulated Cars

For the ‘Space Train’ concept described in Section 7.17, the proposed articulated car bodies were to be mounted on three-axle bogies (Figure 73) (Hope, 1998). The idea was that two frames linked to the bodies on each side of the bogie would be arranged so that all three axles could steer through curves. End bogies would have two axles with only the outer wheelset steered. Clearly, two-axle bogies throughout would be preferable, but they would have been right on the limit for wheel/rail contact stresses.

Wheels were to have a diameter of 430mm. AC motors mounted on the underframe of the car body would drive the outer axles of each articulated bogie. The centre axle would be unpowered because of the reduced space available under the articulation. The motors were to be coupled to the axles by cardan drive shafts, like many diesel trains today.

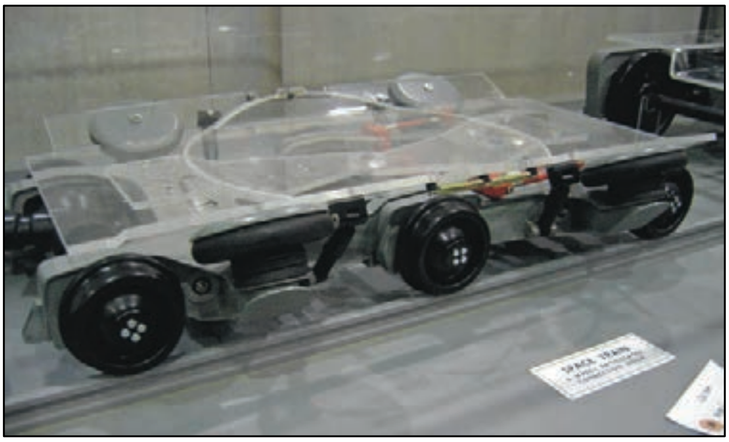


Figure 73: The bogie for the Space Train was a novel, flexible-framed structure with the outer axles driven through cardan shafts by body mounted motors. The centre axle was unpowered. The secondary suspension units were mounted outside the bogie frame and angled inwards to support the car body. Photo: Stephen Knight.

Were this bogie to be constructed with a rigid frame, there is a risk that the Underground track would introduce high stresses in the frame or would cause wheel unloading on track formations with certain combinations of vertical and horizontal curves. The very chequered history of bogie frame performance on the Underground has presented a number of lessons that should be retained by the corporate memory.

8.14 Summary

The development of bogie design for the Underground largely followed the path set by the car body and traction systems in that, apart from the British designed C&SLR, it began with American imports and then these were later adapted by or abandoned by the Underground according to their experience in service.

The case of the original, American designed, cast steel motor bogies (Section 8.4) supplied for both the District and LER tube lines in the 1905-7 period is interesting in that the differing track design of the two railways seems to have had an influence on the performance of the bogies. The District's track was lightly laid and was already 20 or more years old when the line was electrified, whereas the LER track was new and the sleepers were fixed in concrete. The District bogies suffered serious structural problems within a few years of entering service while the tube bogies survived for the life of the stock – up to 25 years. In the author's view, this suggests a clear relationship between track quality and bogie design performance.

Even in recent times, despite over 150 years of development, bogie science is by no means understood sufficiently to prevent some serious problems and failures in design. Both of the batches of sub-surface stock built in the 1960s-70s, the C and D Stocks, have had to have their bogies replaced. Of the tube stocks, the 1983 Stock was scrapped early but would have had to have its bogies replaced as they were the same as the original D Stock design and the 1992 Stock on the Central line also had its bogies replaced by a new design from Siemens. Only the Adtranz designed flexible frame bogie appears to have provided a long term solution (Section 8.9), having now been supplied as a replacement, or for new stock, over a period of 20 years since 1995.

8.15 Conclusions

In terms of what could be learned from the history of bogie development on the Underground after the last 100 or more years, it can be seen that getting a bogie frame to fit under a tube car body and provide sufficient ride comfort is difficult enough but the historically poor quality of much of London Underground track made getting a reasonable ride from the limitations of the suspension in the restricted space even more difficult. With the desire to reduce weight and track forces, future bogie systems will need to be carefully managed if a reliable design is to reach the same 40-year life expected of the car body.

The evidence from the historical perspective shows that more attention needs to be paid to ensuring that bogie design is aligned to the track conditions and its likely performance under the stock for which it is designed. In this area in particular, it is essential to retain the corporate memory of the lessons learned from the expensive bogie replacement programmes carried out over the last 30 years. The difficulties with the welded designs of the 1930s and again of the 1980s, demonstrate that to replace riveted construction with welding both in a largely traditional bogie design and a more modern rigid H-form design, has been found to be inappropriate with poor track conditions. Experience has shown that, in any environment with poor track, welded bogies perform better in a design with a flexible frame format, provided the flexible system is robust enough. This is a lesson that should not be lost from the corporate memory. In future designs, particularly for trains with articulated car bodies, the need for flexibility in the bogie frame should be addressed.

The Circle, District and Central lines have all had bogie replacement programmes at approximately the half-life of recent stock, whereas it should be possible to retain a bogie frame for the life of the stock – 35 years or more. This truism should not be lost on present day railway engineers.

The author considers that the historical evidence shows the importance of a good understanding of the effects of track condition on bogie life and of the need to adopt robust designs in mitigation of track deficiencies. It also shows that, despite many trials and errors, problems with bogie design continue. In the same vein, management attention to track maintenance regimes and their effectiveness in reducing the impact on bogie life will be an important factor in reducing the risk of expensive bogie replacement programmes.

Another lesson learned from the Underground's experience with bogies is that, even with prototyping, as was done for the air suspension system applied to the C Stock in the late 1960s, the apparent success of the design over a few years of testing may not be retained over longer periods.

It is also essential to consider the impact of a new bogie design on the relationship between the train and the structures within which the train moves. The shock sustained by the Underground's operating department, when it realised the 1995 Tube Stock had increased stepping distances over those of the stock it replaced, demonstrated a serious lack of understanding of the impact of the new suspension system on the station operations.

Perhaps the author might be forgiven for saying that a careful assessment of the track and its surrounding structures is essential before adopting a particular bogie design. The lack of this assessment has afflicted the Underground throughout its history. Since much of the riding qualities of a train must be due to track condition, it can be seen that most of the work done by bogies is to try to mitigate the effects of poor track. As any permanent way engineer or rolling stock designer will tell you, money spent on track is not wasted!

9 Discussion

9.1 Introduction

This thesis provides a historical narrative on the development of electric rolling stock on the London Underground system. The narrative was created from a wide range of sources over a long period of research and analysis. The author found that, by researching and analysing the history and development of a large and diverse technological system, it is possible to produce a readable historical narrative that could support decision making in the future development and progress of railway projects. The questions arising from this are whether the narrative is needed by the industry, whether it offers useful lessons for future projects and whether the narrative itself is actually accessible for future projects.

9.2 Literature

In the literature review, the author found a number of writers who described the building up of the corporate memory in the railway industry, how it was based on the need for system continuity and on the desire of staff for secure employment. Some companies demonstrated a desire to retain staff as they realised that experience and on-the-job training were essential for effective and efficient operation. The literature shows that a culture of reliance upon the staff with long service developed and succession plans based on long service or experience were common amongst railway organisations.

The literature showed that, in more recent times, moves into privatisation and the resulting exodus of experienced staff were to change the long service culture and associated succession plans and, with them, there was a loss of corporate memory and a reduction in technical understanding. In addition, short term employment contracts now so common across industry in general, have reduced the capability of a corporate memory to a level where it has caused a reduction in available expertise in the railway business.

The author found that the literature reviewed allowed him to confirm a widely held perception that domain knowledge in the railway industry was weak in some significant areas and a way of overcoming this problem was needed if new project deliveries were to be improved. The author suggested that, if a useful historical narrative could be developed for a railway system and its assets, this could be used to inform future operational and engineering developments.

9.3 Lessons from the Narrative

A major outcome from the narrative is that information is available on how the London Underground railway systems developed. However, time and effort is needed to find, extract and evaluate this information so that a readable historical narrative can be developed. Nevertheless, from this narrative, a number of important lessons are demonstrated and these can have an impact on the railway today and in the future.

One of the lessons shown in the narrative is the need to allow for adaptability. In Chapter 5, the description of the early trials with multiple unit control systems demonstrates that possibly the single most important lesson learned during this phase of electric traction development was that whilst new ideas might seem to solve a problem, it is not always the case when the system is put into service and the engineer must be prepared to adapt his design to suit service conditions or even, in extreme cases like regeneration, defer it until practical operation has caught up with the theory. In parallel, railway clients must expect new systems to require a shakedown period and appropriate time and cost should be allocated for it. The complex new systems introduced for the London Underground at the start of the 20th Century meant that the pioneer engineers and operators were pushed into expanding their experience as their system developed. This phenomenon still occurs today when new systems are introduced and the author argues that sufficient allowance should be made for it in future project plans.

Another demonstration of the need for adaptability is described in Section 6.5 where the Central London Railway was forced to withdraw their newly purchased locomotives and replace them with multiple unit motor cars because of the widespread vibration caused by the excessive weight of the locomotives. This change represented a significant investment increase, forced on the company after only three years of operation but it was also seized upon by the CLR as an opportunity to increase their train service by 25%. The lesson of the value of adaptability is, this example, clearly shown.

9.4 The Value of Prototyping

Throughout this narrative, the value of first testing new systems or new technology in a prototype format has been demonstrated. In the case of the new door control system introduced in 1920 (Section 7.7), a trial took place using one train but it was quickly seen that some of the systems did not function under service conditions and, although it took several months to modify the new trains, the resulting revisions permitted a much more reliable service.

Similarly, in 1936, a radical new tube car design was introduced (Section 6.11) but both the car body design and the new traction equipment was tested in six prototype units before a final selection was made. The result was the iconic 1938 Tube Stock, a design which was to survive for new builds with little change until the 1970s.

Where prototyping was not applied for a radically new system, as in the case of the original District Railway door control of 1905 (Section 7.6), serious operational and safety problems arose and, within three years, the company withdrew the system and converted door operation to manual control. It seems that the value of prototyping was understood when the new door control system was tried in 1920.

In another example, a number of radically new systems were introduced on the 1973 Tube Stock (Section 6.21)without any prototyping and these caused considerable reliability problems that subsequently took 20 years to fully resolve. As a result of experiences of this sort, the author argues that all radical new designs or new systems should undergo a period of prototyping or significant service testing before being accepted for bulk procurement.

9.5 Learning from Failures

The narrative shows how lessons can be learned from failures and it shows how knowledge from these lessons has been lost in some instances. In the case study on the early development of bogie design for the Underground (Chapter 8) it was described how bogie design largely followed the path set by the car body and traction systems in that it began with American imports later either adapted by or abandoned by the Underground according to their experience in service. It showed how there was considerable trouble with bogie design, at least on the District Railway version.

The case of the original, American designed, cast steel motor bogies supplied for both the District and LER tube lines in the 1905-1907 period is interesting in that the author's analysis shows that the differing track designs of the two railways seems to have had an influence on the performance of the bogies. The poor track of the District seriously reduced the bogie life, whereas the LER track was new and the sleepers were fixed in concrete and the tube bogies survived for the life of the stock. The author argues that this suggests a clear relationship between track quality and bogie performance.

Even in recent times, despite over 150 years of development, bogie science is by no means understood sufficiently to prevent serious problems and failures in design. Of recent stocks, two were provided with replacement bogie frames that had to be specially purchased. Only the Adtranz designed flexible frame bogie appears to have provided a long-term solution, having now been supplied as a replacement, or for new stock, over a period of 20 years since 1995.

The author proposes that difficulties with the welded designs of the 1930s, and again in the 1980s, demonstrate that the use of welding both in a largely traditional bogie design and in the more modern rigid H-form design, has been found to be inappropriate for poor track conditions. Experience in recent years has shown that welded bogies perform better on the Underground in a design with a flexible frame format, provided the flexible system is robust enough. This is a lesson that should not be lost from the corporate memory. In future designs, particularly for trains with articulated car bodies, the need for and the design of flexibility in the bogie frame should be carefully addressed.

In terms of what could be learned from the historical narrative on bogie development on the Underground after the last 100 or more years, it can be seen that getting a bogie frame to fit under a tube car body is difficult enough but the historically poor quality of London Underground track made getting a reasonable ride from the limitations of the suspension in the restricted space even more difficult. The evidence from the historical perspective shows that more attention needs to be paid to ensuring that bogie design is appropriate for the track conditions. In this area in particular, it is essential to retain the corporate memory of the lessons learnt from the expensive bogie replacement programmes carried out over the last 30 years.

9.6 Access to Historical Narratives

The writer hopes that his thesis fully justifies the hypothesis that, given suitable research, sufficient time and a structured analysis of the resulting data, it is possible to produce a readable historical narrative for a railway that provides useful information on the railway's asset development and the resulting performance, both in the past and today. In addition, as a demonstration of the power of creating such a narrative, he has provided a number of lessons learned over many years that are still relevant today. However, a formal process is yet to be developed as to how the information and lessons learnt can be stored and accessed in the long term and how they should be used.

Many of the records covering past events and decisions relating to the development of a railway are paper based and it requires considerable time and effort to read these, evaluate them and then create the narrative. Traditionally, the result was produced in the form of a paper or book. With modern word processing, secure data storage and electronic transmittal systems available, it is much easier to distribute a readable and searchable narrative once it has been created. Thus, the author argues, a narrative created today can be made available to a wide audience and may then be used by the organisation and, where appropriate, its suppliers in preparing new system designs or processes. Relatively recently, Network Rail has established a digital repository for historic information from its archives (Network Rail, 2018), which is accessible to a wide range of parties. In a more future orientated approach, Business Information Modelling or BIM (Sacks et al, 2010) is being adopted by a number of organisations, e.g., to manage the information that arises as a major project or programme is being delivered. BIM is powerful because it stores more than just time bound factual information, it also includes the necessary narrative.

A formal method for creating and retaining development narratives must be incorporated into any long-lived organisation's management approaches. Potentially, this could be achieved by adopting classical systems engineering techniques.

9.7 System Engineering as a Corporate Memory Tool

Much of what has been discussed in this thesis is commonly referred to as corporate memory, a term that is known widely but not necessarily understood properly. Conventionally, corporate memory has been seen as being founded in the accumulated combined knowledge of individuals and in such records as a company may have maintained over the years, whether on paper or in electronic form, in archives or readily accessible in a database. Corporate memory is described as, "the combined knowledge and experience of a company's employees" (Cambridge Dictionary, 2018). A synonym for corporate memory is organisational memory. Scalzo (2006) describes organisational memory as "*the knowledge and information from the organization's past which can be accessed and used for present and future organizational activities*". In reality, few organisations put in place a formal process for retaining historic information in a useable format and then maintaining it, i.e., they fail to provide structures and processes that ensure that knowledge is not lost and remains readily available.

The author proposes the use of techniques from the domain of systems engineering, (discussed in Section 3.14 to develop an organisation's corporate memory systematically and to maintain the relevance of the appropriate historic information and narrative in the long term. The process starts with statements of needs that are translated into system requirements as part of a requirements capture process. To be useful for generating corporate memory and narratives, they must be rich requirements, i.e., they must provide full details of all the requirements in well-defined terms, the associated reasoning and the decisions taken for each of the items in the project scope. The requirements are then translated into a specification that is agreed with the stakeholders and also forms part of the narrative.

Change management and rich traceability, two other formal SE tools, can be used to ensure that the corporate memory includes both past and current information and its change history. Each change must be decided formally and agreed with the relevant parties, recorded in detail, complete with the reasons and evidence (data) that led to it and the way in which it was implemented. Rich traceability provides not just a decision history but a documentation that includes the reasons for any decision and change, as well as the parties involved. This approach could be termed ‘rich configuration management’. In the past, paper documents, archives and orally transmitted information provided the foundation for maintaining the corporate memory. Today, this task must be addressed by digital means, e.g., BIM, as mentioned in the previous section. However, digital corporate memory is at risk through obsolescence of databases, storage and access processes, a warning given in the Systems Engineering Book of knowledge (SEBoK, 2017).

SEBok (2017) also notes that, in defining requirements, it must be realised that stakeholder requirements need to be clarified and translated from statements of need into an engineering-based language in order to enable proper definition, design, and verification activities that are needed as part of the system requirements analysis. The author would add that knowledge obtained from the corporate history database should be used to validate the definition and specification of the system requirements.

9.8 Summary

The discussion in this chapter has outlined a number of issues and lessons learnt that were derived from the historical narratives. The discussion points are generated from the case studies on the development of electric traction control systems, the need for improvements to the original car body designs and their passenger access systems and the various designs of bogies. The discussion examined various lessons learnt in rolling stock design and operation over the last 100 or more years and shows the possibility for using a detailed historical narrative to add to corporate knowledge and to assist understanding of existing assets. The discussion also offers proposals related to the use and access of historical narratives as part of a system engineering approach to new projects.

10 Conclusions

10.1 The Research Objectives

This thesis started with a proposition that an accessible historical narrative on past engineering and operational development could be developed and then used as part of a knowledgebase to support an informed, robust strategy for the future development of a railway.

Given this proposition, the aim of the thesis was to demonstrate that, by researching the history and development of a large and diverse technological system like a railway, it should be possible to produce a useful historical narrative to support decision making in the future development and progress of railway projects and to reduce the risk of failings seen in recent times. The historical narrative would be used to aid planning for new systems or installations, guide the introduction of future technologies or the employment of new operational strategies for the railway and provide improved domain knowledge.

In order to achieve this, a series of objectives were developed as follows:

1) To establish a view on the status of the current knowledge of railway systems, corporate learning and organisational development;
2) To locate information that relates to how railway systems on the London Underground were developed since the start of electric traction;
3) To analyse the sources and evaluate them for relevance and context, identify trends in the ways in which systems were developed, the drivers of development and what the results were;
4) To determine if corporate memory loss and path dependency experiences in the wider business and engineering worlds showed any similarity to those the railway industry.
5) To demonstrate that a useable historical narrative that is sequenced, integrated, contextualised and that is accessible, can be produced.

The research for this thesis was based on detailed case studies of various technical aspects of the electric rolling stock on the London Underground railways. Initially, the author looked at the literature on the historical development of path dependency, tacit knowledge resulting from it and the relationships with railway system development. Extensive research has been done to determine the paths of development of train design and equipment over the 125 years since electric traction was introduced on the City & South London railway in 1890.

The analysis demonstrated that a useable historical narrative can be produced and showed clear examples that demonstrate how the use of domain knowledge and the history of development has provided useful guidance for new projects. The narrative demonstrated examples where lessons could have or should have been learned from previous circumstances and other examples where they were learned and applied to new projects.

10.2 Final Conclusions

The thesis demonstrates that a useable historical narrative can be produced. This is not a conventional historiographical study and, whilst it draws upon academic literature on corporate memory loss, it is not intended as a contribution in this field. The principal contribution to knowledge is that it shows clear examples that demonstrate how the use of domain knowledge and the history of development has provided useful guidance for new projects.

In the development of this narrative, certain important aspects of historical railway development that need to be understood and retained in the corporate memory have been shown by the evidence in these case studies to be as follows.

- The long life of rolling stock results in extended periods of improvement stagnation, as shown in car body design (Chapter 7) and traction equipment development Chapter 6);
- Long asset life generates path dependency – once it is known and understood by everyone, it is difficult to go outside the comfort zone and get something radically new;
- There is a need to retain long term technical and operational knowledge at all levels in a railway organisation;
- When historical corporate knowledge is available, it can be used to make sensible decisions on investment;
- Aids on choices of future systems can be gained from in-house experience, past trends and by the use of lessons learned.

It is here argued that the conclusions as listed above show direct pointers towards what might be applied to future railway system design projects. With the life of a rail vehicle under railway conditions that can be as long as 50 years, this points to the need for a clear view of the development and use of that vehicle throughout its life so that the experience can be used and projected forward for future designs. It is argued that this clear view will only be obtained by keeping good records and keeping them up to date, and by using in-house experts who know and understand the system and by educating those joining the railway. It is essential that continuity is provided and that knowledge of the systems is not left to the memories of staff who might easily disappear and take that knowledge with them. Railway business management systems should be modified to include checks throughout a project life so that at least the following aspects of project management are adequately addressed: Electrical, mechanical and civil infrastructure systems integration, rolling stock to signalling compatibility, rolling stock mechanical and electrical integration.

The conclusions in this thesis could be applied to any railway system, although the case studies were on London Underground and the work did not attempt to validate the conclusions other than the ability to research for and create a useable historical narrative.

10.3 Recommendations

The author proposes the following recommendations:

1. The history of assets and of their development should be retained and consulted as part of the normal railway business process.
2. Lessons learned should be published and consulted as part of the normal business process up to board level;
3. New staff should be inducted in the history and development of the railway and its technology, with emphasis on the discipline of the individual as appropriate;
4. Succession planning should include a strategy for long-term staff employment including promotion to senior positions for qualified staff;
5. A risk analysis of a project should incorporate the knowledge developed in the historical system analysis and included in the risk register as appropriate;
6. Organisations must adopt processes that allow the retention of historical narratives and other forms of historical information for use in live projects and processes, including company standards, design instructions, maintenance instructions, systems integration and codes of practice;
7. Teams managing new projects must adopt formal system engineering approaches to ensure that projects absorb historical lessons learned and that generate the knowledge that will support future work by their organisation;
8. New research should be undertaken to validate formally the performance of railway projects that adopt the use of a historical narrative to aid the planning, design and implementation of ongoing and new projects.

These recommendations are not yet common practice and therefore, will have to be developed, tested and implemented. Only once this has been done can they be tested in professional practice.

Through this case study based research, it is shown how the pattern of railway development has shaped the system and technologies and is still doing so today. In fact, it is argued that the railway system is vitally dependent on an understanding of its past in order to succeed in obtaining the most cost-effective solutions for its future development. It is the conclusion that it is essential for railway engineering and operations management to understand the way in which the development of technical and operations has progressed on their railway during its history and that railway business management needs to have this understanding embedded at all stages in their system planning.

Appendix 1:
Auxiliary Equipment on London Underground Trains

Stock	Aux. System	Output	Auxiliaries	Comments
72	MAR (T)	230V AC	115V AC main lighting 60V AC rectifier to 50V DC for control	MAR on 4-car supplies ½ lights on one side of unit.
73	MAR	230V AC	115V AC main lighting 60V AC rectifier to 50V DC for control	MAR supplies ½ lights on one side of unit.
92	Static Converter	230V AC	230V AC for fans; rectifier to 50V DC busline	
95	IGBT Converter	415V AC busline	230V AC fans, traction cooling and rectifier for 50V DC busline	
96	IGBT Converter	415V AC busline	230V AC fans, traction cooling and rectifier for 50V DC busline	
09	IGBT Converter	415V AC busline	415V AC for compressor, fans, traction fans and rectifier to 110V DC for control and lighting.	
D	MAR, FMA	230V AC	115V AC main lighting 60V AC rectifier to 50V DC for control A 230V AC Fan MA is also provided on the trailer of each unit.	MAR supplies ½ lights on one side of unit.
S	IGBT Converter	415V AC	415V AC for compressor, air con., traction fans and rectifier to 110V DC for battery charging, control & lighting.	

Table 4: Auxiliary Voltages on Current LU Rolling Stock.

Notes: MAR = Motor Alternator Rectifier; MAR(T) + MAR mounted under Trailer car; FMA = Fan Motor Alternator on D Stock trailer.

Appendix 2: Lines of the London Underground

Electric Lines of the London Underground

Opening Date	Railway Company	Route	Length in miles	Tunnel Dia.	Traction	Historical Notes
1890	C&SLR	Stockwell to King William St	3.2	10ft 2in & 10ft 6in	Loco, 500v, 3rd rail	Extensions to Moorgate & Clapham 1900, to Angel 1901 and Euston 1907. Connected to CCE&H with 4 rail system in 1924. Extended to Morden 1926. Now Northern Line.
1898	W&C	Waterloo to Bank	1.5	12ft 1¾in to 12ft 9in	Power cars 500v, 3rd rail	Absorbed by L&SWR 1907 and owned by its successors until 1994 when it became part of LU.
1900	CLR	Shepherds Bush to Bank	5.7	11ft 6in	Loco, 500V 3rd rail	Locos replaced by MU traction 1903. Extended to Liverpool St 1912 and Ealing Bdy. 1920. Converted to 4 rail 1938. Extended to W Ruislip, Hainault & Epping 1947-57.
1900	Met. and District	Earls Court to High St Ken.	1.25	25ft	500V 4-rail (outside)	Joint Met./District experimental system. Operated in 1900 only.
1903	District	Acton Town to South Harrow		none	600V 4-rail	Extended to Rayners Lane 1910. Absorbed into Piccadilly line 1933.
1904	GN&C	Moorgate to Finsbury Park	3	16ft	575V 4-rail (outsi	Absorbed by Metropolitan Railway 1913. Converted to 4-rail 630V 1938. Taken over by BR for GN electrification 1975.
1905	Metropolitan	Baker St to Uxbridge	16	25ft	600V 4-rail	Extended to Watford/Rickmansworth 1925, Stanmore 1933 and Amersham 1961.
1905	Met. and District	Circle	13	25ft	600V 4-rail	
1906	H&C	Paddington to Hammersmith		25ft	600V 4-rail	
1905-6	District	Whitechapel to Ealing Bdy., Richmond, Wimbledon		25ft	600V 4-rail	Extended to East Ham 1906 and Barking 1908. Upminster 1932.
1906	BS&W	Elephant to Baker St.	3.6	11ft 8¼	600V 4-rail	Extended to Edgware Rd. 1907, Paddington 1913, Queens Pk. 1915 and over L&NWR to Watford 1917. Extended over Metropolitan line to Stanmore 1939. Cut back to Queens Pk.
1906	GNP&B	Hammersmith to Finsbury Park		11ft 8¼	600V 4-rail	Extended to S. Harrow 1932, Cockfosters and Uxbridge 1933 and Heathrow 1977, T5 2008.
1907	CCE&H	Charing Cross to Hampstead & Golders Green		11ft 8¼	600V 4-rail	Extended to Edgware 1924. Connected to C&SLR 1926, Extended to High Barnet 1940.
1913	East London Railway	Shoreditch to New X & New X Gate		25ft	600V 4-rail	Committee management and operated by Metropolitan Railway. Taken over by Network Rail for rebuilding in 2007.
1968	Victoria Line	Walthamstow to Victoria		12ft	600V 4-rail	Extended to Brixton 1972.
1979	Jubilee Line	Stanmore to Charing Cross		12ft	600V 4-rail	Took over Bakerloo branch Baker St to Stanmore. Extended to Stratford 1999.

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