Overhead Line Electrification for Railways

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Front Cover: Faiveley CX PG monoband pantograph, under Mark 3b tramway OLE at St Pancras International, UK
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1. Foreword

Since the earliest days of railways it has been obvious that it is senseless to haul the power plant around with the train. Isambard Kingdom Brunel clearly understood this. He realised that not carrying the weight of the steam engine gave significant advantage. Never one to pass by the opportunity to be in the vanguard of technical novelty, in 1840 he took on the building of the South Devon Railway over the Devon Banks. Seduced by the possibilities that technology used by the London and Croydon Railway offered, he advised the use of the “Atmospheric System”. This used fixed steam engines to create a vacuum, and a 15 inch diameter pipe between the rails. A slot with a seal in the top of the pipe allowed a piston attached to a tow truck to be pushed along by atmospheric pressure.

Ignoring the reservations of his great locomotive Engineer, Daniel Gooch, the obvious railway operation limitation of a system only operable as a single line, and the folly of relying on greased leather as the only available way to seal the top of the tube around the mechanical connection between piston and truck, Brunel gambled the South Devon shareholders’ capital. The decision drove that company to near bankruptcy, presented Gooch with the problem of building powerful enough locomotives to haul the trains and left us to this day with a line so aggressively graded and curved that train speeds remain severely restricted.

It is easy to dismiss the attempt to build a railway needing no self-powered locomotives as an act of hubris, but Brunel was in fact right; hauling the source of motive power is restrictive of train speed, causes more rapid degradation of the rails and track supports and is energy inefficient. Mid-19th century technology was unable to realise Brunel’s ambition, and it was not till 20 years after his death that the eventual solution began to emerge.

In 1879 Siemens and Halske demonstrated a technology destined to mature into electric traction. Siemens had produced an electric locomotive picking up electrical supply from fixed conductors at the side of the track.

Various systems for electric traction emerged; conductor rails on the ground and overhead lines were developed in various forms, some more successful than others. Whenever analysis has been undertaken through the last century, electric traction has always been found superior. But there is another theme which runs constantly through that history. Whilst the benefits of electrification of a railway are beyond debate, the capital cost of the fixed equipment and the service disruption involved in building the system leave no margin or fat in the cost benefit case. For that reason, in the UK electrification of the main line railways, which started in the late 19th Century, is still not complete.
In this book Garry Keenor shares his widespread and deep knowledge making a great contribution to helping equip future generations of Engineers and Designers to understand the intricacies of electric traction overhead line. The text and examples are presented in such a clear and practical way that the book should be indispensable for beginners new to the discipline through to those with much longer experience.

With better background knowledge Engineers and Designers can produce better results. The challenge that all of us who dedicate our working lives to the traction electrification discipline face is to keep the cost of electrification at a point where the economics work. The case for finally providing a practical solution over the Devon Banks is again in play with electrification widely seen as the only viable option. That railway, and other main line railways need affordable solutions. For the Engineers and Designers who must rise to meet that challenge this book will help in their laudable task.

Peter Dearman
November 2018
2.  Preface to the 4th Edition

The genesis of this book lies in a presentation I gave in 2003. Carillion (my client on a major resignalling scheme) asked for a lunchtime session on overhead line electrification, since most of their staff were unfamiliar with the system; and for the first time in my life my ego won out over my fear of public speaking and I accepted. The request for 30 minutes of material was soon forgotten in my new-found enthusiasm for powerpoint, as I proceeded to cram all my knowledge at that point into a file which grew to more than 70 slides.

The final product came in at over two hours, and I knew I was in trouble. Luckily my client was understanding and arranged to extend the session. I’m glad to say that my audience were also in forgiving mood, and most of them were still awake at the end. However, I had learned an important lesson: don’t overstay your welcome on the stage.

So, having stripped back the talk for future sessions, I needed somewhere to put the more comprehensive material. I had always been struck by the paucity of accessible literature around the subject; when I was entering the industry at the tender age of 19, I was handed a slim booklet titled “Railway Electrification: 25kV a.c. Design on B.R.”¹, and that was it. At the other end of the scale there is of course the standard text on the subject, “Contact Lines for Electric Railways: Planning, Design, Implementation, Maintenance”²; but although fearsomely comprehensive (and expensive), even the most able engineer would not describe it as an easy read.

I therefore resolved to write something which would provide an approachable and reasonably comprehensive study of overhead contact systems, which would explain the why as well as the what, aimed at people with a basic mechanical and electrical knowledge who are new to the topic. In essence this is the book I would like to have been given when I joined British Rail as a graduate trainee. At the end of the book you will not be able to undertake all the tasks involved in OLE design, but I hope you will understand what needs to be done and why.

I am always nervous when an experienced colleague asks for a copy of the book, perhaps for one of their trainees. I do not pretend that everything is covered, and the book is inevitably biased towards my experience, which is predominantly 25kV AC systems in the UK. It is also exhibits a bias towards the mechanical side, with the electrical sections being less comprehensive.

¹ Booklet is available online at www.railwaysarchive.co.uk/docsummary.php?docID=2
Additionally, this year’s best practice can quickly become last year’s unwise experiment, and so it is necessary to refresh the book from time to time.

3. Preface to the 5th Edition

The 4th edition was the first to be placed in the public domain, and I was naturally keen to get it published after months of preparation. A number of additional topics warranted inclusion, but some items weren’t ready in time for publication – like so many engineers I have a troubled relationship with deadlines. The 5th edition includes these new sections and is (I think) the first complete version – in terms of topics at least.

New or greatly expanded sections are as follows:

- Section 9.4 – immunisation;
- Section 9.10.1 – AC earthing & bonding;
- Section 9.10.2 – DC bonding & stray currents;
- Section 9.11 and Appendix B – dual voltage areas;
- Section 10.1 and Appendix C – pantographs;
- Section 10.8 – isolators;
- Section 10.10 – structure loadings;
- Section 10.16 – materials;
- Section 10.17.5 and 10.17.6 – ancillary conductors and other wires;
- Section 10.18 – wire connections;
- Section 11 – signage;
- Section 12 – types of UK equipment;
- Section 13 – special arrangements;
- Section 17 – testing and commissioning;
- Section 19 – remote condition monitoring.

This edition also includes a large number of new and improved images and diagrams.

It also affords the opportunity to correct several errors pointed out by readers of the 4th edition. However new material means new potential for errors, so corrections or clarifications are always gratefully received at garry.keenor@gmail.com, or via twitter where I am @25kV.

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3 The errata list for this version and all previous versions is available online at www.ocs4rail.com/uncategorized/current-errata-list
The positive reception to the 4th edition has been gratifying, and it is always nice to see a copy on someone’s desk in a design or project office. I hope you will find this edition just as useful.

4. Acknowledgements

A full list of all the people who have trained, coached and cajoled me over the years would run to several pages. The following people in particular have provided me with invaluable knowledge at various points in my career, and without them I could not have written this book:

Erik Bates, Graeme Brindle, Alan Clegg, Paul Hooper, Russell Jackson, Shaun Leatherbarrow, Allen McDonald, Rob Tidbury, Andy Ward, Anne Watters, Mick Whelan, Dr Roger White, and the late David Ingrams.

The responsibility for any errors remains (as always) with me and me alone, but there would be far more of them without the generosity of colleagues in agreeing to check the new material. In particular I’d like to thank Brian Armstrong, Rob Daffern, Dave England, Andy Gardner, Ed Mellor, Sanchay Singhal and Dr Roger White for their review and critique of the new and heavily revised sections.

Various colleagues and online friends have kindly given permission to use their images – a full list of credits is contained in the Table of Figures. Particular thanks are due to Morris Line Engineering for permission to use their isolator images.

The knowledgeable people who inhabit the OLE group on Facebook have clarified a number of items for me, particularly in relation to Appendix D, and provided historical knowledge which is not available anywhere else.

Peter Dearman did me the huge honour of writing an excellent foreword – without doubt the only time that my name will appear on the same page as Brunel’s; and for that I am very flattered and grateful.

Simon Warren kindly repeated his roles as overall proof-reader for this edition, and as always was remarkable unflustered when the 300 page draft landed on his desk.

Finally I must of course thank my wife Claire for indulging my endless rail-related waffle, and daughter Chloe for keeping my ego in check.

Garry Keenor
Wiltshire
2018
5. How to Use This Book

This book gives an introduction to overhead line electrification systems for railways, and covers all types of railway and Overhead Line Equipment; all developments are covered, together with examples of UK systems. It applies to all overhead power supply systems for tram systems, light and heavy rail, low speed and high speed.

The book assumes a basic knowledge of maths and mechanical and electrical engineering concepts. All new terms are explained as the book goes along, and the explanation of a term is indicated by italicised text. Occasionally a term is unavoidably used earlier in the book, without explanation, in which case a cross-reference is provided, like this: (section 4). For those reading the document on-screen, these are clickable hyperlinks. Most images are high resolution and will benefit from zooming into the PDF.

Most PDF software has a search function triggered by typing [ctrl]+f – this is an easy way to find a reference from anywhere in the book.

Within the book the following terms are used:

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beyond</td>
<td>Object A is beyond Object B when a train passes Object B before Object A</td>
</tr>
<tr>
<td>DMU</td>
<td>Diesel Multiple Unit</td>
</tr>
<tr>
<td>EMU</td>
<td>Electric Multiple Unit</td>
</tr>
<tr>
<td>High speed</td>
<td>Speeds above 200kph</td>
</tr>
<tr>
<td>Heavy rail</td>
<td>Traditional railway systems; as opposed to light rail and tram systems</td>
</tr>
<tr>
<td>On approach to</td>
<td>Object A is on approach to Object B when a train passes Object A before Object B</td>
</tr>
<tr>
<td>Overbridge</td>
<td>A bridge over the railway</td>
</tr>
<tr>
<td>Underbridge</td>
<td>A bridge under the railway</td>
</tr>
</tbody>
</table>

Wires are referred to by their layup; that is, the number of strands and diameter of each strand. For instance, 19/3.25 wire comprises 19 strands, each 3.25mm in diameter. Elements and alloys are denoted by their periodic table symbol, or similar abbreviation, as follows:
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>Silver</td>
</tr>
<tr>
<td>Al</td>
<td>Aluminium</td>
</tr>
<tr>
<td>Bz</td>
<td>Bronze</td>
</tr>
<tr>
<td>Cd</td>
<td>Cadmium</td>
</tr>
<tr>
<td>Cu</td>
<td>Copper</td>
</tr>
<tr>
<td>Mg</td>
<td>Magnesium</td>
</tr>
<tr>
<td>Ni</td>
<td>Nickel</td>
</tr>
<tr>
<td>Si</td>
<td>Silicon</td>
</tr>
<tr>
<td>Sn</td>
<td>Tin</td>
</tr>
<tr>
<td>Zn</td>
<td>Zinc</td>
</tr>
<tr>
<td>HD</td>
<td>Hard Drawn (generally applied to copper)</td>
</tr>
</tbody>
</table>

A footnote with the reference *ibid* means it is referring to the same document as the previous reference.
6. Basics of OLE

6.1 What is OLE?

Overhead Line Equipment (OLE) is a system used to deliver continuous electrical energy to a stationary or moving train, by means of a sliding contact between on-roof current collection equipment and a fixed overhead supply conductor. It is also known in the UK as OHL or OHLE. In Europe & the US, it is known as Overhead Contact System (OCS), and in New Zealand, as Overhead Wiring System (OWS). The generic term for the system is Overhead Contact Lines.

This book will use OLE, as it is the preferred term in the UK.

6.2 Unique Features of OLE

Unlike other power transmission systems, OLE is required to transmit high power\(^4\) to a stationary or moving load\(^5\) at a distance of several miles. The contact wire is therefore a twin system – it functions as both power transmission mechanism and sliding contact with the train.

The key requirement for any OLE system is to provide continuous power to the train. For this to happen there must be continuous contact between OLE and the pantograph (section 10.1). Loss of

\(^4\) Up to 10MVA per train

\(^5\) The current railway speed record is held by a French TGV unit, which reached 574.8kph on 3 April 2007 travelling under modified and super-tensioned (40kN) 31kV OLE. Video is available online at www.youtube.com/watch?v=wflI-5h6Rg8
contact leads to degradation of energy transfer and unwelcome damage to the contact wire and pantograph due to electrical arcing.

OLE is a very exposed system, being vulnerable to climate – especially wind, snow and ice; to wildlife – particularly birds; and also to pollution and vandalism. The mechanical and electrical forces imposed on OLE by repeated pantograph passages and heavy starting traction loads are significant; and these make unplanned events much more likely than in conventional transmission lines. OLE systems must therefore be capable of withstanding frequent electrical fault conditions without degradation of performance. The system tends to be constrained by other railway infrastructure, particularly in the UK where it has been retrofitted to railways built in the 19th century with small clearances above the train.

Due to the continuous contact requirements, the contact wire position is critical to successful operation. There is no redundancy in this part of the system; a second contact wire is not a practical proposition, from either an engineering or financial standpoint. If the contact wire strays outside defined position limits, the pantograph will usually damage a significant length of the OLE before the train comes to a halt.

Figure 2: OLE/pantograph damage at 70kph

Video is available online at www.youtube.com/watch?v=XgCPPeYmyKw

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6 Video is available online at www.youtube.com/watch?v=XgCPPeYmyKw
OLE is above all else a combined electrical and mechanical system, and the requirements of each must be balanced in the design.

6.3 Advantages and Disadvantages of the System

The key advantages of OLE systems over train-borne traction systems such as diesel or gas-turbine can be summarised as:

- Higher acceleration\(^7\) and braking due to lower weight and ability to exceed rated power for short periods – meaning greater capacity on routes with frequent stops;
- Lower rolling stock capital cost\(^8\);
- Lower rolling stock operational costs, largely as a result of fuel costs\(^9\);
- Lower rolling stock maintenance costs\(^10\) - \(^11\), due to the much smaller number of moving parts;
- Greater train reliability\(^12\), for the same reasons as above;
- Smaller fleet requirements due to increased reliability, since fewer trains are out of service for maintenance;
- Lower track maintenance costs\(^13\), driven by lower track forces from lighter power units;
- Elimination of diesel particulate pollution at the train, along with associated health hazards\(^14\);
- Flexibility of energy source (assuming a national grid generation mix which allows the railway to buy energy appropriately);

\(^7\) Typical rate of acceleration is 0.65m/s\(^2\) for DMU, 1.0m/s\(^2\) for EMU. "Study on Further Electrification of Britain’s Railway Network"; 2007; RSSB/Atkins; Appendix D

\(^8\) UK diesel vehicle capex is on average 12% higher than for electric vehicles. "Rail Value for Money Study – Rolling Stock Whole Life Costs – Final Report"; 2011; Arup; figs 2.10 and 2.11

\(^9\) For instance on the UK’s West Coast franchise, diesel fuel accounts for 40% of total traction cost, despite only 15% of the fleet being diesel. “Electrification Benefits”, Shirres; October 2017; Rail Engineer

\(^10\) DMU maintenance costs across Europe are typically 40% higher than for an EMU. “European Benchmarking of the Costs, Performance and Revenues of GB TOCs – Final Report”; 2012; Civity; p65

\(^11\) DMU maintenance costs worldwide are twice as high as EMUs. “Benchmarking identifies good practice in rolling stock maintenance”; 2006; Railway Gazette

\(^12\) A new UK EMU has an average miles per technical incident of 26906, against 10272 for a new DMU – more than 2½ times as reliable; a midlife UK EMU is still almost twice as reliable as the most reliable equivalent DMU. “Understanding the Rolling Stock Costs of TOCs in the UK”; January 2015; Steer Davies Gleave; section 4.51

\(^13\) Typical track wear and tear costs are 15% higher for diesel vehicles than for electric vehicles; “Network Route Utilisation Strategy - Electrification”; Network Rail; 2009; table 3.3

\(^14\) “A Breath of Fresh Air: New Solutions to Reduce Transport Emissions”; January 2018; IMechE; p17
- Reduced greenhouse gas emissions, and concentration of emissions at a single source enabling more efficient control\(^{15}\)\(^{16}\);
- Lower energy usage through regenerative braking (up to 20% is recovered);
- Reduced noise and vibration, improving passenger comfort levels.

It should be noted that OLE has the advantage over ground-mounted conductor rail transmission system at higher speeds – conductor rail systems are limited by current collection requirements to about 160kph with current technology, and bring their own safety issues.

Set against this are the disadvantages of the OLE system:

- High capital cost of installation;
- Lack of redundancy in the contact wire;
- Management of safety risks from high voltages.

![Figure 3: OLE damage causing major disruption; Bethnal Green, UK](image)

\(^{15}\) Electric trains produce 20% to 36% less carbon dioxide emissions than diesel trains, although these values are affected by the fuel source of the electric power generation. "Study on Further Electrification of Britain’s Railway Network"; 2007; RSSB/Atkins; table 3.2

\(^{16}\) Use of low carbon energy in the UK grid is rising; in Q3 2017 54.4% of energy came from low carbon sources, up from 50.2% in Q3 2016. "UK Energy Statistics, Q3 2017"; December 2017; Department for Business, Energy and Industrial Strategy; p1
Because of the high capital cost of OLE, it has historically been difficult to gain funding for new electrification schemes, especially in the UK. Railway finances adhere to the timeless dictum that money ultimately comes from only two sources: the taxpayer and the fare payer. It is usually national or local government that authorises electrification schemes, and they will only proceed if two conditions can be demonstrably met:

- That there is a reasonable return on their citizens’ investment – in other words, that the capital outlay is paid for by reduced operational expenditure over a reasonable period of time;
- That the scheme can be built within the ceiling of available funding.

For this reason the focus of the planner, designer and installer must be to deliver a reliable system which minimises the whole life cost of the equipment (including maintenance and unplanned disruption costs), but not at the expense of an affordable capital outlay.
7. Development of OLE systems

The following sections give an overview of the history of OLE development. For a more detailed list of UK builds, see Appendix A.

7.1 Electric Beginnings

The first OLE systems were used with passenger trams in the last years of the 19th century. These generally consisted of a simple single wire (trolley or tram) system, suspended from poles and buildings, and fed at a low voltage. This was preferred to the previous attempts with 3rd rail systems, which gave rise to both reliability and safety problems in congested on-street areas.

The first thirty years of the 20th century saw these principles extended to mainline systems as the advantages of OLE over 3rd rail became clear. As volt drop losses increased with distance, voltages were increased to compensate. At the same time, more sophisticated suspension systems were required to maintain good current collection at increasing linespeeds (section 10.2). At this time the national grid had not been developed, so railways often had their own power stations feeding at a variety of voltages and frequencies.

Figure 4: 6.7kV AC twin catenary simple OLE on the London, Brighton and South Coast Railway; circa 1910
Experimental AC schemes were implemented for the Lancaster to Heysham (1908) and London Victoria to London Bridge (1909) schemes, both at 6.7kV, 25Hz AC. AC motor technology was not mature at this time, necessitating complex train-borne rectification equipment, which gave reliability problems of its own. AC traction did not make any further headway in the UK until after World War Two.

In the north of England the Newport – Shildon line, which featured heavy coal trains running over steep gradients, was electrified with 1500V DC OLE in 1915.

### 7.2 Mainline DC Growth

The barriers to using AC, coupled with the transmission limitations of DC current, meant OLE was only used for suburban and freight systems, where heavy electrical loads and short distances meant DC OLE made economic sense. In the UK, 1500V DC OLE was agreed in the 1930s as the national standard. The Sheffield to Manchester and Wath route, which required very heavy coal trains to be hauled over the steep gradients of the Derbyshire peaks, was authorised for electrification in 1939, as was the Great Eastern Mainline (GEML) out of London Liverpool Street. However World War Two brought this, and all other electrification schemes in Europe, to an abrupt halt.

![Figure 5: Sheffield – Manchester route, with 1500V DC OLE](image)

Both schemes recommenced after the war, but by now the railways’ priority was rebuilding their battered infrastructure rather than funding new schemes. The Wath scheme was completed in

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17 “Electric Railways, 1880 – 1990”, Michael C Duffy; 2003; IEE; p74

18 Ibid., p263
1952, but was a pyrrhic victory, since within 6 years the DC standard was obsolete. The line survived until 1981, by which time it was an isolated system. The GE lines fared better due to their essential commuting status, eventually being converted to 25kV AC.

The story of OLE in the UK during the first half of the 20th century is a faltering one, but the rest of Europe installed a large amount of 1500V DC in the pre- and post-war years, and much of this network still exists.

7.3 AC Developments

The 1950s saw increased interest in AC OLE, driven by the emergence from the electricity supply industry of reliable industrial frequency technologies. This meant that high voltage, long-distance AC transmission – and by inference, inter-city OLE – was now feasible. Experiments with 50Hz AC traction had first been made as early as 1940 in Germany. Across Europe, as the 1950s progressed the 1500V DC standard was dropped in favour of 25kV at AC industrial frequency; in the UK this was approved as the standard for future schemes (using 50Hz AC) in 1956.

The Lancaster to Heysham route, which had pioneered HV AC OLE in 1908, was converted from 25Hz to 50Hz in 1951 to serve as a test bed for industrial frequency. These tests confirmed the choice as the right one. A further test scheme was installed between Colchester and Clacton in 1959. Various types of OLE were trialled, including simple and stitched equipment (section 10.2), but compound equipment was chosen as giving the best current collection at speed.

It was initially assumed that 25kV AC systems would require significant electrical clearances to existing infrastructure, and so 11” (275mm) was adopted as the standard air gap for bridges. In the UK this meant major reconstruction work, particularly for the many bridges in the vicinity of large stations, so for these areas a reduced voltage of 6.25kV was proposed, with 4” (100mm) clearances. Trains would be dual-voltage and switch between them on the move as necessary, using neutral sections each side of the bridge.

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20 “Electric Railways, 1880 – 1990”, Michael C Duffy; 2003; IEE; p321
21 Ibid.; p273
22 Paper; A D Suddards, T H Rosbotham, T B Bamford
23 “Electric Trains in Britain”, B.K. Cooper; 1979; Ian Allan Ltd; p43
Experience on the Great Eastern (GE) lines out of Liverpool St, where the 1500V DC lines were converted to 6.25kV AC, showed that there was excessive caution in the standard clearances. Reduced clearances, and later special reduced clearances (section 9.8) were added, so that 25kV could be adopted throughout.

The West Coast Mainline (WCML) electrification was the first large scale 25kV scheme in the UK; it was planned to have 6.25kV sections, but in light of GE experience was implemented fully at 25kV. The dual voltage locomotives which had been built for the route were modified as single voltage machines, and the 6.25kV areas were converted to 25kV.

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24 “Electric Railways, 1880 – 1990”, Michael C Duffy; 2003; IEE; p322
The first phase of the West Coast scheme was extremely successful in operational terms; it brought about a step change in service speed, and revived an image of high speed rail travel last seen in the 1930s. This came to be known as the “sparks effect”.

However the railways were facing increasing pressure from an expanding motorways network, not to mention worsening finances, and when British Rail (BR) proposed a rolling programme of mainline electrification schemes, the Ministry of Transport made it clear that costs would have to come down.

BR responded with a wholesale overhaul in the design of OLE. The heavy, bespoke portal arrangements of the West Coast equipment were abandoned in favour of a new, lightweight, modularised, headspan-based metric system (the Overhead Line Equipment Master Index or OLEMI – see section 12.1.7). The first OLEMI system was known as Mark 3, and was further developed as Mark 3a; in this form it was used on the second phase of West Coast from Weaver Junction through to Glasgow in 1974.
7.4 High Speed Lines

Elsewhere in Europe, the possibilities for higher speed passenger trains using electric traction began to be explored. The French state railway SNCF began a series of experimental runs in the 1950s, culminating in a record-breaking run reaching 326kph in March 1955. This used a modified 1500V DC system, with the line voltage increased to 1900V by means of mobile substations. The record stood until 1981. The tests showed the obstacles to be overcome if speeds over 300kph were to become the norm. Frictional heat caused the pantographs to collapse; track damage was so great that derailment was only narrowly avoided.

Figure 8: Track damage after 1955 high speed run; France

Japan was the first country to build an electrified mainline railway from scratch. The Tokyo - Osaka Shinkansen (‘New Trunk Line’) opened in 1964. This was segregated from existing lines, and used 25kV 60Hz AC OLE rather than the 1500V DC used elsewhere in Japan. The line had no level crossings and was designed for continuous high speed with linespeeds of up to 210kph.

Figure 9: 0 series Shinkansen; Japan

France continued to develop their high speed system, and the *Ligne à Grande Vitesse* (LGV) concept was born. This would use dedicated high speed lines, high powered trains and a 50kV Auto Transformer system (section 9.4.3). Gradients were relatively steep, since the high power available meant that expensive embankment and cutting works would be minimised.

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25 Ibid.; p389
The first LGV between Paris and Lyon (TGV Sud-Est) opened in 1981. Since then, additional lines have been opened, and the concept has been exported to Germany (as the ICE), the UK (High Speed One) and worldwide.

7.5 UK – APT and HST

In the mid-1960s BR began to investigate higher passenger speeds. Financial constraints ruled out LGV-style solutions, meaning any improvements would have to be delivered on existing routes. The newly-formed BR research division set themselves a target to achieve 250kph speeds and a 40% increase through curves on the West Coast Mainline. The result was the *Advanced Passenger Train* (APT), which used active tilt to provide the required levels of passenger comfort through curves, as well as a host of other new technologies. Articulated bogies were used, where carriage ends sat on a single bogie, thus improving ride quality. Two stage hydraulic/air brakes were used to improve braking performance. The pantograph was linked by chains to the bogie, thus countering the tilt of the train body.

Development of APT was prolonged – the gas turbine APT-E prototype ran until 1976, and the electric production model did not appear until 1978. While the project had obvious promise, many of the traditionalists in BR engineering were not convinced that the research division’s gamble would pay off. The APT programme also ran into trouble with the unions, since the prototype did not have a second seat for double-manning.

The Traction & Rolling Stock Division were convinced they could push diesel technology to provide sustained high speed running, and began to develop the *High Speed Train* (HST) concept.
This pushed diesel traction design to the limit to produce a 200kph fixed length diesel train, for use on the Great Western Mainline (GWML).

The train surpassed all expectations and set the standard for high speed passenger services for decades to come. The HST took the world speed record for a diesel train, reaching 232kph on 12 June 1973, a record not surpassed until 2002. The project was so successful that the HST build was extended to provide higher speeds on the East Coast Mainline (ECML) and Midland Mainline (MML). This effectively stalled the mainline electrification program – in the case of ECML, by 10 years, and GWML and MML by 40 years.

On 20 December 1979 an electric APT took the UK speed record from HST, reaching 259kph. However the complexity of the train proved to be its undoing. Major teething problems were encountered when the train entered service in 1981, and this was compounded by some ill-advised press runs leading to bad publicity, and the worst weather seen in years that winter. By 1984 BR were on the point of solving the technical problems, but political backing for the project had evaporated and funding was stopped.

![Figure 11: APT tilting on neutral section tests; Murthat, UK](image)

APT was ultimately a failure of political will rather than technology. The lessons learned were taken by Italian train builders, who developed the Pendolino concept, successfully used throughout Europe – and now, ironically, sold back to the UK as for use on the West Coast Mainline.

7.6 Privatisation and Beyond

Electrification proceeded in the UK through the 1980s, albeit on smaller schemes such as St Pancras – Bedford and Colchester – Ipswich. BR was finally given the go-ahead in the mid-1980s to
continue electrifying the ECML north of Hitchin, and this was completed in 1991. However, budgetary constraints meant the OLE on this scheme had a weak power supply, and the OLE design was prone to failure.

Infill schemes continued in the 1990s, with Cambridge to King’s Lynn, Carstairs to Edinburgh and London to Heathrow Airport all completed. A significant milestone was the opening of the Channel Tunnel, operating at 160kph with OLE. However privatisation had broken the link between infrastructure capital cost and train maintenance saving which was vital to justify the initial cost of electrification schemes. The splitting of rolling stock procurement, rolling stock operation and infrastructure ownership led to a huge increase in diesel procurement, as no organisation would benefit from the whole life advantages of electric traction.

By the early years of the 21st century the only major schemes in progress were the West Coast upgrade, and the Channel Tunnel Rail Link (CTRL), which finally brought true high speed (300kph) running to the UK. Section 1 of CTRL opened in 2003, and section 2 into London was opened in 2007. This line has now been renamed High Speed One.

On 30 July 2003, a Eurostar test train took the UK rail speed record from the APT, reaching 334.7kph (208mph) on section 1 of CTRL.

The middle part of the 2000s saw the beginnings of renewed interest in OLE in the UK, as a surge in oil prices, increasing environmental pressure, and new diesel emissions regulations all affected the economics of diesel traction. In 2010, with both the HST and the associated signalling systems
approaching life-expiry, the UK government committed to a new programme of electrification on the GWML, as well as the Midland Mainline and routes in the North West. This programme proceeds as I write – although not without some difficulties – and the first sections of North West and Great Western Electrification schemes are now in public operation.

Figure 13: A Hitachi IET forms the first electric train to run on the Reading-Didcot section of Great Western on 17 July 2016; Cholsey, UK
8. Categories of OLE System

The parameters of an OLE system must be matched to the railway to which it is to be applied. OLE systems fall into one of five broad categories.

8.1 Tram Systems

Trams are mass transit systems, used to move large volumes of people over relatively short distances at relatively low speeds (up to 80kph), usually in and out of urban centres. These systems feature on-street running, tight radius curves, steep gradients, short headways between trams and line of sight driving (i.e. no signalling except at highways interfaces). They are usually of post-war vintage.

Tram OLE system design is driven by the need to ensure the safety of the public, and by the many interfaces with buildings and highways. The systems are low voltage (usually 750V DC) and are often split into on-street and off-street equipments; the former being characterised by high contact wire, fixed termination tramway equipment (sections 10.2 and 10.3) and support from buildings, and the latter by a more conventional system with catenary and auto-tensioning (section 10.3). Support assemblies are very light, and double insulation (section 9.10.2) is used to prevent stray currents from entering buried services.

Figure 14: Typical street-running tram with building-suspended OLE; Birmingham, UK
8.2 Trolley Systems

Trolley buses also provide mass transit, and are used to provide low-pollution electrified public transport without the high cost and disruption of laying rails in city centres. The system consists of an unguided trolley bus controlled and steered by a driver in the same way as a conventional bus, but powered via OLE which is usually suspended from adjacent buildings.

![Trolley bus system, showing complex double pole insulation and tight radius curve; Lucerne, Switzerland](image)

Figure 15: Trolley bus system, showing complex double pole insulation and tight radius curve; Lucerne, Switzerland

Uniquely for an OLE system, the lack of running rails means that traction current cannot return to the supply point using the rail. Therefore the OLE is a double pole system, with outward and return contact wires insulated from earth and each other. These provide both circuit legs, and a pair of pickup poles on top of the trolley bus collect and return traction current. The double pole arrangement leads to additional insulation complexity wherever routes converge or diverge.

Trolley bus systems are popular in continental Europe, and share many common features with tram systems. In some cities such as Bern the two types of transport run on a common support system.
8.3 Light Rail Systems

Light rail systems are a step up from trams. They are also mass transit systems, situated in and around urban centres, but they do not feature on-street running, and share many of the characteristics of heavy rail, such as fixed signalling. Speeds are usually below 120kph.

For these systems, supply voltages are higher (1.5kV DC or 25kV AC), and the OLE is often fixed termination, with simple catenary (section 10.2). Structures and assemblies are lightweight, and headspans (section 10.11.7) are often used. The Tyne & Wear Metro is an example of such a system.

![Figure 16: Typical 1500V DC metro; South Hylton, Tyne & Wear, UK](image)

8.4 Mainline Systems

Mainline systems form the bulk of the OLE railway route mileage worldwide. These systems are mainstream traditional railways; speeds may be anywhere up to 200kph, and traffic may be heavy and frequent, with a mix of passenger and freight. The railway may date from Victorian times, the OLE having been superimposed at a later date.

Standard supply voltages are 1.5kV or 3kV DC, and 15kV or 25kV industrial frequency AC (25kV being standard for all systems since the 1960s). OLE is either simple or compound auto tensioned (section 10.2 and 10.3); assemblies are heavier, and portal (section 10.11.6) or headspan (section 10.11.7) structures may be used. Fixed termination equipment (section 10.3) is often used in sidings and terminal stations.
8.5 High Speed Systems

Mixing passenger services with slower moving freight at speeds above 200kph is neither practical nor safe. For this reason, high speed systems are usually dedicated to passenger services; the high power available often means steep gradients are used, reducing construction costs. These lines are usually less than 40 years old, and built with generous OLE clearances. Service speeds are typically 300kph or 350kph.

The standard supply voltage is 25kV industrial frequency AC, usually with a transmission voltage of 50kV and an Auto Transformer system (section 9.4.3). Good current collection becomes paramount; OLE is either sagged simple, stitched simple or compound (section 10.2). Assemblies are lightweight, and structures are a mix of portals and cantilevers (section 10.11.1).

Figure 17: Typical high speed railway; Class 374 on High Speed One; Sellindge, UK
9. Electrical Principles

9.1 Supply voltages and currents

9.1.1 Transmission and Supply Voltages

*Transmission Voltage* is the voltage at which energy is transmitted to the train’s location. *Supply Voltage* is the voltage at which the train is supplied with energy.

For the majority of systems, the transmission and supply voltages are the same. However, some high speed lines use a higher transmission voltage to avoid excessive volt drop losses and thus provide more power at the train.

A variety of supply voltages are used around the world, due to a combination of historical and operational factors. 750V DC is standard for tram systems, and is chosen to minimise safety issues in public areas. 25kV AC, at a frequency equal to the country’s industrial supply frequency (50Hz in the UK), is used for the majority of new mainline and all new high-speed builds. Most countries (with the notable exception of the UK) have a legacy network of 1500V DC OLE, and Northern Europe has a sizeable legacy 15kV AC 16.7Hz network.

It should be noted that the supply voltage is not a single constant value, since volt drop losses, magnitude of load in section and other factors affect the supply voltage at the train. For instance, below are the allowable voltages for UK 25kV AC systems.\(^{26}\)

<table>
<thead>
<tr>
<th>System Voltage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5 kV</td>
<td>Minimum voltage at which a train should continue to operate for not more than two minutes without being damaged. Equipment energised from the overhead line need not continue to operate if the voltage falls below 12.5kV, but should not be damaged.</td>
</tr>
<tr>
<td>14 kV</td>
<td>Minimum voltage at which a train should continue to operate for not more than ten minutes without being damaged. Also the voltage below which regenerative braking should cease.</td>
</tr>
</tbody>
</table>

\(^{26}\) NR/GN/ELP/27010 “Guidance for Compatibility Between Electric Trains and Electrification Systems”, Issue 2, December 2005; Network Rail; section 4.2
### System Voltage

<table>
<thead>
<tr>
<th>System Voltage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.5 kV</td>
<td>Minimum voltage in normal operation. If the voltage falls below this value it should not be possible to initiate regenerative braking</td>
</tr>
<tr>
<td>20 kV</td>
<td>Minimum constant current voltage value</td>
</tr>
<tr>
<td>24 kV</td>
<td>Average voltage for use in train performance calculations</td>
</tr>
<tr>
<td>25 kV</td>
<td>Nominal system voltage</td>
</tr>
<tr>
<td>27.5 kV</td>
<td>Maximum voltage at which train equipment should operate continuously</td>
</tr>
<tr>
<td>29 kV</td>
<td>Train equipment should be able to operate without suffering damage if the voltage rises to this level for 5 minutes</td>
</tr>
</tbody>
</table>

Each system will have a line voltage performance specification in this way, and the OLE system design is tailored to meet this.

#### 9.1.2 Supply Current

The supply current is dependent upon the train power characteristic and the number of trains in section at any one time. For Low Voltage (LV) DC systems, the supply current is relatively high.

<table>
<thead>
<tr>
<th>Train Type</th>
<th>Typical Train Starting Current Draw</th>
</tr>
</thead>
<tbody>
<tr>
<td>750V DC three car tram</td>
<td>~ 1100A</td>
</tr>
<tr>
<td>750V DC train</td>
<td>~ 3000A</td>
</tr>
<tr>
<td>1500V DC train</td>
<td>~ 1500A</td>
</tr>
</tbody>
</table>

For AC systems, the higher voltage available means lower supply currents.

<table>
<thead>
<tr>
<th>Train Type</th>
<th>Typical Train Starting Current Draw</th>
</tr>
</thead>
<tbody>
<tr>
<td>25kV AC passenger train</td>
<td>~ 200A</td>
</tr>
<tr>
<td>25kV double headed freight train</td>
<td>~ 500A</td>
</tr>
</tbody>
</table>
Of paramount importance is the maximum fault current – the highest current which will flow under fault conditions. The entire OLE system must be designed to withstand many such faults over the lifetime of the equipment, without degradation of the components. For UK classic 25kV systems (section 9.4), the maximum fault current is 6kA. For AT systems (section 9.4.3), an increased level of 12kA is generally specified.

Figure 18: Ends of contact wire which has parted during an undetected 25kV fault

9.1.3 AC Supply Principles

AC systems do not require rectification equipment, and AC electrical arcs are easier to extinguish when they cross zero volts, which means they can use higher voltages than DC. The resultant percentage volt drop is much lower, and so feeder stations can be further apart than for DC systems – for a standard 25kV feeding system, feeder stations are 40 to 60km apart. This eliminates the requirement for a separate HV feeding network.

Supplies have traditionally been obtained at each feeder station from the 132kV Distribution Network Operator (DNO). 25kV is obtained through 132/25kV transformers supplied by the DNO. These are often duplicated to give a backup supply or redundancy. These transformers are usually procured by the railway but owned and maintained by the DNO. They may be sited at a DNO compound alongside the railway feeder station, or sited at a remote DNO site with 25kV cabling between the two.

New UK installations are now taking their supplies from the 400kV Electricity Supply Industry (ESI – also known as National Grid Company or NGC) system, with a much reduced load imbalance and therefore much greater power capacity (section 9.4.3). By the mid-2020s it is possible that mainline rail will be the biggest single consumer of electricity in the UK.
The single phase supply taken from the three phase system at each feeder station creates an unbalanced load (or phase imbalance) on the ESI system. The ESI imposes contractually agreed limits on its customers on the total imbalance, and the railway is usually the biggest single contributor to this imbalance. For example, the ESI UK limits are 1.5% on the grid or DNO; and 0.5% maximum contribution by the railway. This is one of the key reasons for moving to a 400kV-derived supply for high power railways.

Figure 19: Feeding a single phase railway from a three phase ESI

To help limit the imbalance, adjacent feeder stations use different phase combinations; for instance feeder station 1 uses red-blue, feeder 2 uses blue-yellow, feeder 3 uses yellow-red. Direct connection of these adjacent systems would be catastrophic, so a short section of dead OLE – a neutral section – is used to keep the phases electrically separate. Trains shut off power before the neutral section, usually by means of an automatic trip, and coast through the neutral section before the power is switched on again (section 10.7.3). This configuration is single end fed, with all power coming from one supply point, and uses tee-feeding, with each feeder station supplying power in two directions.

Some administrations are now exploring the use of Static VAR Converters (SVCs) to eliminate national grid imbalance, and with it neutral sections. These solid state devices are able to convert 3 phase AC into single phase AC with a high level of efficiency. Other administrations – notably Russia – use 3 phase transformers between grid and railway to reduce the imbalance.

The OLE between feeder stations is electrically split into sections and subsections, allowing sections of OLE to be isolated during planned maintenance or emergency situations. Each running line is

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electrically separate from the others. For classic feeding, sectioning is maintained at intermediate locations called *Track Sectioning Cabins* (TSCs) or *Track Sectioning Locations* (TSLs). These are the equivalent of the Track Paralleling Hut on a DC railway (section 9.5), and help keep the system impedance down by paralleling all OLE circuits together. The *midpoint TSC* (MPTSC) – so called because it is midway between feeder stations – includes a neutral section which keeps the phases at adjacent feeder stations apart. Each feeder station also has a neutral section, allowing the phase split to be moved up and down the railway in emergency feeding conditions. AT systems work on similar principles, but the equivalent of TSCs and MPTSCs are known as *Auto Transformer Sites* (ATS), *Sectioning Auto Transformer Sites* (SATS) and *Midpoint Auto Transformer Sites* (MPATS).

A typical classically fed sectioning arrangement is shown overleaf. Typical spacings for 25kV classic feeding are:

- Feeder Station to Feeder Station – 40 to 60 km;
- Feeder Station to midpoint TSC – approximately 24km;
- Feeder Station to TSC – approximately 11km.

Spacings are determined by the traffic to be handled, the train performance requirements and the electrical characteristics of the overhead and supply systems. These considerations result in an optimum spacing which it is not often possible to achieve in the real world, and shorter sections are often used to locate the feeder stations at strategic points such as junctions or route intersections. Feeder Stations are usually situated in close proximity to grid substations in order to avoid the high cost of long incoming feeds.
Figure 20: Typical feeding arrangements for classically-fed AC OLE
AC Supply Equipment

Feeder Station, TSC and AT Site Formats

Feeding and sectioning compounds are unmanned, and take a number of different forms. Until the 1970s the standard format was a fully enclosed brick building housing all the circuit breakers (section 9.2.4), protection (section 9.7.1) and SCADA (section 9.7.2) equipment. However this format needed costly civil engineering, so alternatives were sought.

In the 1970s the modular steel housing format was developed; this used a steel building module of standard section, typically housing one circuit breaker, so that multiple modules could be bolted together to form a substation.
However this method still required significant foundation work, and so in the 1980s the building was done away with altogether, in favour of *Structure Mounted Outdoor Switchgear* (SMOS). This placed all the circuit breakers in special outdoor housings, mounted on OLE structures with a bare aerial busbar. The SCADA equipment was contained in a small building.

However this type of installation created its own problems; water ingress has occurred in circuit breakers, particularly in regions prone to bad weather. In the 1990s the SMOS concept was replaced by the *containerised building* concept, where a complete substation (apart from the transformers) is fitted out in a factory environment and delivered to site in a steel building. This remains the preferred format in the UK, either with indoor switchgear, or more recently with the containerised building housing control equipment for SMOS.

![Figure 22: Modular steel feeder station; Elvanfoot, UK. Note incoming DNO supply on right](image1)

Figure 22: Modular steel feeder station; Elvanfoot, UK. Note incoming DNO supply on right

![Figure 23: SMOS track sectioning location; Kings Norton, UK. Circuit breaker arrowed](image2)

Figure 23: SMOS track sectioning location; Kings Norton, UK. Circuit breaker arrowed
9.2.2 AC Transformers

AC transformers are used to step voltages down from 132kV or 400kV to the supply voltage. They are typically of a conventional oil-filled naturally-cooled design. Off load tap changing of ±2½ and 5 percent is normally provided to allow the output voltage to be adjusted, but transformers with remotely controlled on-load tap changing are sometimes installed to allow this adjustment to be made in service. Transformers are generally supplied in standardised sizes:

- 15 MVA/600A;
- 10 MVA/400A;
- 7½ MVA/300A;
- 5MVA/200A.

Where AC supplies are derived from networks operating at voltages lower than 66kV, (such as 33kV or 11kV) the transformers are usually purchased by the railway infrastructure owner.

Many administrations require oil-filled transformers to incorporate a means to mitigate the environmental damage done if the oil escapes in the event of a transformer failure. This typically takes the form of a concrete bund incorporated into the transformer footing, big enough to house the total volume of oil in the transformer tank.
9.2.3 Auxiliary Transformers

Auxiliary supplies are often taken from the OLE at a Feeder Station or TSC, either to supply local Low Voltage (LV) equipment or as a backup to other supplies. Auxiliary supplies can be for:

- Signalling Supplies (typically 650V or 400V);
- Battery charging (typically 110V);
- Operation of switchgear;
- Lighting;
- Heating.

These supplies can be derived from the traction supply by means of step down transformers, or direct from a DNO feed.
9.2.4 AC Circuit Breakers

*Circuit Breakers* are designed to interrupt the traction supply during fault conditions or for routine maintenance. They must be capable of closing and opening (*making* and *breaking*) with both the normal operational currents (*load current*) and the much higher currents experienced during a fault. They must be able to do this many times over their life without experiencing degradation of the electrical contacts. Of particular importance is the ability to quickly extinguish the electrical arc which forms as the contacts move apart.

![Figure 27: Oil Circuit Breaker; Rugby, UK](image)

AC circuit breaker technology has advanced significantly in the last 50 years, and this is reflected in the range of circuit breaker types on the railway. In historical order of installation, they are:

- Oil insulated;
- Air insulated;
- Vacuum insulated;
- Sulphur Hexafluoride (SF$_6$) insulated for both the arc chamber and general insulation;
- Hybrid – vacuum for the arc chamber and SF$_6$ for general insulation;
- Air insulated (again).

*Oil Circuit Breakers* (OCBs) were used for installations until the 1970s. Oil provides a good electrical insulator and will extinguish the arc quickly while dissipating the heat generated. However, they are heavy and bulky, and are not able to clear faults quickly, while repeated operations contaminate the oil with carbon deposits. These further degrade performance, meaning regular maintenance – which is messy and time-consuming – is required.

*Vacuum Circuit Breakers* (VCBs) were first used in the 1970s. Their simplified mechanical arrangement means they were thought to be more reliable than OCBs, giving improved interrupting capacity, increased contact life, and requiring less maintenance. They are also significantly quieter and smaller than OCBs, and require less maintenance.
Sulphur Hexafluoride (SF₆) breakers were introduced because the vacuum in VCBs was proving hard to maintain, with frequent leaks occurring. Initially SF₆ was used for both insulation and arc-extinguishing purposes, but it was found that under arcing conditions the gas breaks down into acidic elements which damage the breaker.

More recent SF₆ designs have used the gas for insulation only, with a vacuum used for extinguishing the arc. However SF₆ is considered to be the most potent greenhouse gas to enter our atmosphere, and the search is on for a suitable replacement.

**Figure 28: ABB vacuum/SF₆ SMOS circuit breaker, Kings Norton, UK**

Recent developments have looked at the use of resin, or even a modern form of the oil-filled circuit breaker. New UK installations are currently using *Air Insulated Switchgear* (AIS). This requires more space than SF₆ or vacuum types but is more reliable and has no environmental disadvantages.

**Figure 29: SF₆ circuit breakers; Patford Bridge, UK**

### 9.2.5 AC Cables

Incoming 400kV or 132kV supplies from the DNO are typically delivered to the railway feeder stations through 400-500mm² two-core *concentric pressure* cables. The same type of cable is also used where connections are required between railway feeder stations.
Generally the cables are of the oil-filled type, with some being gas-filled. This latter type has the advantage of a lower charging current, and is favoured for tunnel use. Connections from the switchgear to the 25kV overhead contact system are usually formed of 25kV single core solid type cables. These cables must be carefully routed to prevent damage to the insulation; the cable will typically be laid in protective troughing, a minimum bend radius is specified\(^{28}\) and additional protection measures may be specified as the cable transitions from trough route onto a mast.

**Figure 31: Sealing ends at a Sectioning AT Site; Swindon, UK. Note the cable armour taken to earth on the middle sealing end**

The transition from insulated cable to bare wire requires a specialised assembly known as a sealing end, which facilitates connection of a bare lugged wire while sealing the insulated cable against water ingress or damage. These connections are built in the field, and the process requires skill

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\(^{28}\) For 400mm\(^2\) cable, minimum bend radius is typically 1.5m
and care\textsuperscript{29}, they must be electrically pressure tested (section 17.3) to ensure that the insulation strength is maintained.

\section{9.3 AC Sectioning Principles}

Sectioning is carefully chosen to give the ability to isolate any OLE section, and is matched to the normal and perturbed working train service patterns.

Crossovers are usually provided to allow trains to transfer from the normal running line to the \textit{wrong direction} line under \textit{perturbation conditions}. Traditionally in the UK insulators have been placed in the OLE (section 10.4) to create subsections which are bridged by normally-closed isolators. When these are opened they allow the OLE to be isolated at a fault. The train then runs wrong direction around the isolated subsection.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{sectioning_diagram.png}
\caption{Traditional sectioning of perturbation crossovers}
\end{figure}

\textsuperscript{29} Installation video is available online at \url{www.youtube.com/watch?v=rlqHW9HmYA}
A serious disadvantage of this arrangement is that the Points of Isolation are not at the same location on both tracks. This leaves a residual hazard when one track is isolated; the other remains live and this gives rise to an electric shock risk for workers.

New electrification in the UK is now using parallel isolation points; these also allow the whole junction to be isolated for maintenance, but are less flexible under perturbed working.

Isolators have traditionally been manual, requiring switching on site, but remotely operated motorised isolators are increasingly used.

**Figure 33: Parallel sectioning of crossovers**

### 9.4 AC Feeding and Immunisation Methods

The first OLE systems used the OLE to transmit power to the train, and one or more running rails to return current to the supply point. Since the rails and sleepers form a conductive path to earth, a portion of the return current will flow via the general mass of earth.

In AC systems this was found to be unsatisfactory, due to the large electromagnetic (EM) field created around the OLE. This drives inductive coupling which creates particular problems for safety-critical lineside signalling and telecoms cables.

Any conductor carrying current will generate a magnetic field whose strength is proportional to the current, and this field induces a voltage in any nearby cables which is proportional to the magnetic field strength seen by that cable and the length of the cable, in accordance with Faraday’s Law. The proportion of return current flowing in the rails (as opposed to via earth) decreases exponentially with distance from the supply point\(^\text{30}\), and this current is shared between the running rails as a result of cross bonding (section 9.10.1). For this reason each rail generates a much weaker EM field and so the OLE EM field dominates, creating an induced voltage in any lineside cables\(^\text{31}\). This longitudinal voltage will drive a current that is able to form a circuit via the

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\(^{30}\) NR/GN/TEL/31106 “Overview of Electromagnetic Coupling between Traction Systems and Telecommunications Cables”, Issue 1, 2009; Network Rail; section 6.3

\(^{31}\) A 200A train load with 10km of parallel lineside cable and no mitigation will induce a longitudinal voltage of 154V in the cable. Ibid., section 7.1.1
capacitance of the lineside cable to earth. If the lineside cable has an outward and return conductor (typically formed as a twisted pair) then small variations in the longitudinal voltage will create a transverse voltage between the conductors. This voltage appears as noise on the cable and creates interference in telecoms systems. Inductive coupling can also affect sensitive magnetic systems in nearby universities, factories and hospitals.

![Diagram](image)

Figure 34: Induced currents in lineside cables with non-immunised OLE

Various techniques have since been adopted to manage this risk.

### 9.4.1 Classic Feeding – Return Conductors Only

Where current-carrying conductors interact, the relative direction of the currents determines whether the magnetic fields add or subtract from one another. At any point the magnetic fields can be summed to determine the resultant magnetic field. This interaction is exploited by the Return Conductor (RC) system.

The RC runs parallel to the OLE, at approximately the same height, and positioned over the lineside. The RC is insulated from the OLE masts and bonded at regular intervals to the running

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32 Ibid.; Section 6.6
rail, so providing a measure of current sharing\textsuperscript{33}. Because the current in the RC flows in the opposite direction to that in the OLE, and is at equal height, the magnetic field produced by the RC will act to reduce the field produced by the OLE at ground level by around 50%. However, the currents and therefore the fields are not equal, and there is still the potential for interference.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure35.png}
\caption{Reduced induction in lineside cables with Return Conductor\textsuperscript{34}}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure36.png}
\caption{(l-r): Magnetic and electric fields for RC-only railway\textsuperscript{35}}
\end{figure}

\begin{itemize}
\item \textsuperscript{33} Around 35\% of return current will still flow via earth, and a 200A train with 10km of parallel cable will induce around 76V. Ibid.; section 7.1.2
\item \textsuperscript{34} Cable capacitance and cable return flow omitted on this and all subsequent immunisation diagrams for clarity
\item \textsuperscript{35} “Report on the Application of the Control of Electromagnetic Fields at Work Regulations 2016”, Rafi, Gavrilakis, Hayes; 2016; Atkins/RSSB; Appendix A
\end{itemize}
To maximise cancellation of the magnetic field it is necessary to transfer all of the return current from the rail to the RC. This is achieved by means of a *Booster Transformer* (BT). A BT is a 1:1 ratio current transformer, with the primary winding connected in series with the OLE so that traction current is routed through it. The secondary winding of the BT is connected in series across an electrical break in the RC. The current in the primary induces an equal and opposite current in the secondary winding, and so in the RC; and this current can only come from the rail at a bond connection midway between BTs called the *midpoint connection* (MPC).

This system ensures that almost all return current moves from rail to RC. Since the current in OLE and RC are now approximately equal and opposite, the magnetic fields at ground level largely cancel each other out, and so the BT/RC system provides a large measure of immunisation for lineside cables\(^{36}\).

**Figure 37: Midpoint Connection from RC to traction return rail; Edinburgh, UK**

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\(^{36}\) A 200A train with 10km of parallel cable will induce around 12V. NR/GN/TEL/31106 "Overview of Electromagnetic Coupling between Traction Systems and Telecommunications Cables", Issue 1, 2009; Network Rail; section 7.1.3
Booster Transformers are typically located every 5km, and OLE overlaps (section 10.4) are used as a convenient point for a break in the OLE.

37 Ibid.; section 7.1.3
Booster transformer systems have two major disadvantages: the transformers require regular checks, particularly for contamination of the insulating oil; and they increase the impedance of the system, thereby limiting the power capacity.

The BT/RC arrangement has been used widely across Europe, Asia and the UK, but there remain a large number of legacy RC only routes. The BT/RC circuit is shown overleaf.
Figure 41: Booster Transformer arrangement for OLE
9.4.3 Auto Transformer Feeding

There are practical limits to the amount of power that a BT system can deliver as volt drop losses increase. In particular, the move to higher passenger speeds requires a system with much higher power availability. The Auto Transformer (AT) system was pioneered at Philadelphia in the US in the early 20th century, using 36kV transmission and 12kV supply. It was then used on the Shinkansen at 60kV:30kV, before being introduced in Europe for TGV routes at 50kV:25kV. This is now the standard configuration for new high speed lines, and the details below are based on this configuration.

In any electrical circuit with a fixed load, power is proportional to $V^2$, and so there is more power available in a 50kV system than in the classic 25kV feeding system. Alternatively, since the current is halved for the same power, the same electrical load can be serviced with fewer feeder stations spaced further apart.

Figure 42: Simplified AT Feeding

The heart of the system is the Auto Transformer itself. This is a 1:1 ratio 25kV-0V-25kV centre-tapped current transformer, with the OLE fed from one half of the winding at +25kV, and an Auto Transformer Feeder or ATF (also known as an Auxiliary Feeder or AF) fed from the other half at -25kV. The traction return rail (section 9.10.1) is connected to the 0V centre tap. The ATF also carries out a similar immunisation role to the Return Conductor.

Delivery to the train is at 25kV as normal – a key requirement of any AT system, which must interface with traditional systems and trains. A proportion of the train current comes directly from the feeder station via the OLE, and this varies with distance from the feeder station; the rest comes from adjacent AT sites, using current induced in the OLE by the -25kV half of the ATs. Essentially the AT sites act as proxy feeder stations, and are typically located every 8km.

The additional 25kV ATF conductors create additional design challenges, since 25kV clearances must be maintained for ATF to earth, but also 50kV clearances for ATF to OLE. This can be a particular problem through limited clearance overbridges and stations.

The AT system is widely used on high speed systems worldwide, and in the UK it is installed on HS1 and on the WCML and ECML, where it has been retrofitted to increase power capacity. New installation is under way on the GWML. The AT arrangement is shown overleaf.
Figure 43: Auto Transformer arrangement for OLE

Actual current proportions will vary with train location, and values given are for illustration only.
Figure 44 (top to bottom): Magnetic field strength midway between Auto Transformers, and at an Auto Transformer with 100A train load\textsuperscript{38}

9.4.4 Boosterless Classic Feeding

In recent years the BT/RC system has been deprecated in the UK, in favour of boosterless classic feeding. This arrangement removes all booster transformers and return conductors in favour of a simple out-and-back feeding arrangement. Immunisation is instead provided by means of a Return Screening Conductor (section 9.4.5).

9.4.5 Mutual Screening and Return Screening Conductors

The Mutual Screening Conductor (MSC) and Return Screening Conductor (RSC) systems exploit another feature of electromagnetic fields interacting with conductors. Both take the form of an

\textsuperscript{38} Ibid.; section 7.1.4
insulated cable placed immediately next to the cable which requires immunisation – usually in the signalling trough route.

When used as an MSC, this cable is earthed – in the UK, this is done every kilometre using a 4Ω earth connection. The EM field created by the OLE then acts on the MSC, setting up a magnetic field which opposes that of the OLE in accordance with Lenz’s Law. Current will then begin to flow in the MSC, in the opposite direction to the current in the OLE. The MSC cable size is chosen with a larger cross sectional area than the lineside cables to provide a lower impedance, so the AC induced current in the MSC will be correspondingly higher than that in the lineside cable.

The induced current in the MSC then creates its own magnetic field in the trough route which induces a voltage in the lineside cable; one which opposes that induced by the OLE. This works provided that the MSC has low impedance to earth, and is physically close to the lineside cable.

MSCs in the UK are typically PVC sheathed 19/3.25 Aluminium cable (section 10.17.5). This provides a screening factor of about 0.69, meaning the voltage induced on the LV cable is reduced by 31%. Although the current induced by the MSC is lower than that induced by the OLE, the reduction can sometimes be sufficient to remove the safety risk.

The disadvantage of the MSC is that it needs earth farms at regular intervals along the railway, and provides only limited screening. The RSC operates in the same way as an MSC, but is instead
connected to the traction bonding system, typically at the cross bond locations (section 9.10.1). This removes the expensive earth farm requirement and provides significantly better screening than an MSC – for example the same 19/3.25 Al cable provides a screening factor of 0.33, reducing the induced voltage by 66%.

![Image of railway electrification system]

**Figure 46: Minimised induction in lineside cables with Return Screening Conductor**

RSCs are now being used in the UK with Boosterless Classic and AT feeding systems. Although the ATF in an AT feeding system provides a measure of EM cancellation, an RSC is also used to allow lineside circuit lengths to be significantly longer.

### 9.5 DC Supply Principles

DC systems have historically been constrained to lower supply voltages (up to 3kV) due to the expense and availability of *rectification equipment* (which converts AC current to DC), and the difficulty in breaking DC fault current. This means the system suffers from a large volt drop as a percentage of the supply voltage, and substations must be placed close together (1.5km to 6km apart). The cost of providing a direct feed from the DNO at each location would be prohibitive, so mainline DC railways usually have a dedicated HV trackside feeder system to provide power to the substations. These feeder rings are typically at 66, 33, 22 or 11kV, fed from a 132kV DNO infeed. The HV supply is then transformed down and rectified at each substation to provide power to the railway. The rectifier is fed with all 3 phases, meaning there is no imbalance on the DNO supply or requirement for neutral sections. The removal of any phase imbalance allows DC systems to be *double end fed*, which helps to raise voltages midway between substations. DC
substations have outputs varying from 1MW (for tram systems) to 10MW (for mainlines). Regenerative braking is only possible on DC systems with the addition of a DC to AC inverter in parallel with the rectifier.

Many mainline DC systems also have traction feed wires; these run at the same voltage as the OLE and connect to it at regular intervals. They are usually suspended from the OLE structures and help to reduce the system impedance and raise line voltage.

Tram systems are usually compact enough not to require HV feeder rings, which would in any case be difficult to safely configure in busy street environments. They do however usually have traction feed cables buried in lineside ducts for safety reasons, and brought up the mast at regular intervals to connect to the OLE.

### 9.6 DC Sectioning Principles

Switching is carried out at intermediate Track Paralleling Hut locations. These help keep the system impedance down by paralleling all tracks together.

A typical DC sectioning arrangement is shown overleaf.

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Figure 47: Typical feeding arrangements for DC OLE
9.7 Protection, Monitoring and Control

9.7.1 Fault Protection

OLE systems are vulnerable to a large number of faults. These faults create currents that are much larger than those caused by normal operation, causing considerable damage if the supply is not quickly disconnected. To prevent this damage an electrical protection system is used to clear faults by opening the circuit breakers feeding into the section.

Any system of protection should:

- Be sufficiently sensitive to detect a fault in its early stages;
- Be very reliable in operation – the simpler and more robust the design the better;
- Discriminate between currents fed to faults within the section being protected, and current passing through to a fault in another section.

OLE is split into sections that are fed from one (AC) or both (DC) ends. Each feed is routed through a circuit breaker. Attached to this by means of a Current Transformer (CT) and Voltage Transformer (VT) is a relay which looks continuously for faults, by measuring the impedance of the section that it is feeding. This is known as impedance or distance protection. It exploits the fact that fault current will usually flow through several circuit breakers between the fault and the feeder station, thus giving the opportunity to provide time delayed backup protection.

Figure 48: Optimho AC distance relay; Patford Bridge, UK

For instance, UK AC OLE has three zones of protection: zone 1 is instantaneous and is set to the impedance of the initial section less a calculation tolerance; zone 2 sees approximately 70% of the next section and has a small time delay; and zone 3 sees all of the next section with a larger time delay.

To understand how this works, consider a system consisting of three series sections, each protected separately and capable of isolation by a circuit breaker at the feeding end:
The fault at F is a section fault relative to Section C, but a through fault relative to Sections A and B. Thus the protective devices on Sections A and B should not trip their respective circuit breakers, whilst the protection on Section C should open its circuit breaker.

If circuit breaker C does not clear the fault within the specified time, then the protection on section B will cause circuit breaker B to trip. Similarly, circuit breaker C will act if circuit breaker B does not.

In addition to impedance protection, overcurrent and undervoltage protection may be provided. These systems will respectively protect the OLE against overload, and trains against undervolts.

### 9.7.2 Control and Monitoring

The circuit breakers at feeder stations, TSCs and AT sites are under the control of the Electrical Control Room (ECR). This is a control centre which supervises operation and maintenance of the OLE. A telecommunication system known as Supervisory Control and Data Acquisition (SCADA) is used to monitor and control circuit breakers remotely. Traditional railway SCADA use a Time Division Multiplex (TDM) system which polls each feeder station in turn, interrogating the state of each circuit breaker. Any change in state or alarm is relayed back to the ECR. Similarly the ECR can send an instruction to a particular circuit breaker to open or close in the event of a fault or maintenance. The Electrical Control Operator (ECO) is therefore able to monitor and control the whole system from a set of display screens at a central terminal. Motorised switches under ECO control may also be provided at key locations if fast perturbation management is required.
TDM systems are now being superseded by computer-based systems, using *Internet Protocol* (IP) based networks and computer outstations in each switching site. These sites are capable of communicating with each other to determine and clear faults, without needing direction from the central ECR software. They do this by means of *Generic Object Oriented Substation Event* (GOOSE) messages.

This system is captured in a new European standard\(^\text{40}\), and has the potential to revolutionise the detection and clearance of faults.

\(^{40}\) IEC 61850:2018 “Communication networks and systems for power utility automation”; International Electrotechnical Commission; 2018
9.8 Electrical Clearances

Since it is not possible to provide insulated conductors in an OLE system, it is essential for safety and reliable operation to keep all live OLE parts a sufficient distance from other infrastructure, so that *flashover* is prevented.

For this reason two sets of air gap clearances are defined. The *static electrical clearance* is the clearance which must be achieved under permanent (static) conditions. The *passing electrical clearance* is a smaller clearance which must be maintained for a short duration as the train passes or another transient event occurs. This smaller clearance is justified by the lower risk level in a short-duration event.

These clearances are set for a particular system voltage, based on the *insulation coordination*\(^41\) for the system. This involves selection of the right level of insulation strength to provide protection against both supply voltages and transient overvoltages, such as those experienced during lightning strikes\(^42\). The *lightning impulse withstand voltage* is typically an order of magnitude higher than the supply voltage, and is also the determining factor in the size of insulators (section 10.19).

It is usual to have several categories of static and passing clearance in recognition of the different circumstances which may apply. For instance, historically UK standards\(^43\) defined four clearance categories;

- *Enhanced Clearances*, used wherever practicable;
- *Normal Clearances*, used where enhanced clearances cannot be attained;
- *Reduced Clearances*, only to be used with the consent of the infrastructure owner when normal clearances cannot be attained;
- *Special Reduced Clearances*, only to be used with the consent of the safety authority when reduced clearances cannot be attained.

\(^{41}\) Insulation coordination in European systems is specified in BS EN50124-1:2017 “Railway Applications – Insulation Coordination Part 1: Basic requirements - Clearances and Creepage Distances for all Electrical and Electronic Equipment”; 31 March 2017; BSI; section 5.2

\(^{42}\) A typical lightning withstand voltage for 25kV AC systems is 200kV. If an air gap or insulator breaks down under lightning strike conditions, the resulting arc will allow traction fault current to flow.

\(^{43}\) GE/RT8025 “Electrical Protective Provisions for Electrified Lines”; Issue 1, October 2001; RSSB; section B4.6.2
The reduced level was introduced in 1962 based on operational experience and experimental findings; and the special reduced level was introduced in 1974 based on further testing and the introduction of a stress-graded bridge arm (section 10.11.9)\(^44\).

The historical standards for the various voltage standards used in the UK prior to 2015 were as follows:

<table>
<thead>
<tr>
<th>System Voltage</th>
<th>Clearance</th>
<th>Enhanced</th>
<th>Normal</th>
<th>Reduced</th>
<th>Special Reduced</th>
</tr>
</thead>
<tbody>
<tr>
<td>750V DC(^45)</td>
<td>Static</td>
<td>≥75mm</td>
<td>75mm</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Passing</td>
<td>≥25mm</td>
<td>25mm</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>1500V DC(^45)</td>
<td>Static</td>
<td>≥500mm</td>
<td>150 – 499mm</td>
<td>100mm</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Passing</td>
<td>≥500mm</td>
<td>≥100mm</td>
<td>99 – 80mm</td>
<td>N/A</td>
</tr>
<tr>
<td>25kV AC(^46)</td>
<td>Static</td>
<td>≥600mm</td>
<td>270 – 599mm</td>
<td>269 – 200mm</td>
<td>199 – 150mm</td>
</tr>
<tr>
<td></td>
<td>Passing</td>
<td>≥600mm</td>
<td>≥200mm</td>
<td>199 – 150mm</td>
<td>149 – 125mm</td>
</tr>
</tbody>
</table>

For AC systems this standard has been superseded by a new Group Standard\(^47\) which introduces three levels of insulation; reinforced insulation (equivalent to the old enhanced level) provides the highest level of protection, basic insulation provides an acceptable level, and functional insulation (equivalent to the old normal level) provides a level which must be supported by a risk assessment. The old reduced and special reduced levels are not formalised but remain available in extremis.

\(^{44}\) “Railway Electrification: 25kV a.c. Design on B.R.”; 1988; Director of Mechanical & Electrical Engineering, British Railways; section 4.2
\(^{45}\) HS(G)153/4 “Railway Safety Principles and Guidance, Part 2, Section C: Guidance on Electric Traction Systems”; 2005; HSE; section 43
\(^{46}\) GE/RT8025 “Electrical Protective Provisions for Electrified Lines”; Issue 1, October 2001; RSSB; section B4.6.2
\(^{47}\) GL/RT1210 “AC Energy Subsystem and Interfaces to Rolling Stock”; Issue 1, December 2014; RSSB; section 2.1.8.1, table 5
<table>
<thead>
<tr>
<th>System Voltage</th>
<th>Clearance</th>
<th>Reinforced Insulation</th>
<th>Basic Insulation</th>
<th>Functional Insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>25kV AC</td>
<td>Static</td>
<td>≥ 600mm</td>
<td>370 – 599mm</td>
<td>270 – 369mm</td>
</tr>
<tr>
<td></td>
<td>Passing</td>
<td>≥ 200mm</td>
<td>≥ 200mm</td>
<td>≥ 200mm</td>
</tr>
</tbody>
</table>

Where reinforced insulation cannot be provided, such as at low overbridges, a section of contact wire typically replaces the catenary. This minimises the chance of wire stranding in the event of a flashover. This wire is known as *catenary*.

**Figure 52: Catenary wire damage caused by electrical arcing; Rayleigh, UK**

It is possible to reduce air gap clearances further by providing overvoltage protection by other means, reducing the air gap to a level sufficient to withstand the supply voltage. This can be achieved using a *Surge Diverter* (also known as a *Surge Arrester*). This device is a type of *Non-Linear Resistor*, and is connected between the OLE and traction earth. At normal operating voltages it is an insulator and prevents current flowing to earth. However if the voltage in the system reaches the threshold (typically set 50% higher than the supply voltage) the surge divertor becomes a conductor, allowing current to flow safely to earth rather than arcing across the air gaps in the system.
This approach to reducing air gap clearances at overbridges is now on trial in the UK.

9.9 Safety Separations

The sliding contact function of OLE means that protection by insulation is not practical when it comes to protecting the public and staff from the risk of electric shock. Instead, protection by separation\(^{48}\) is extensively used. This means maintaining minimum distances between places that people can access – standing surfaces – and all live parts. These safety separations are considerably larger than the electrical clearances for a given system. For instance, the minimum safety separation between a standing surfaces and fixed live parts for 25kV AC lines in the UK was for many years 2.75 metres. This has now been increased to 3.5m. It is only possible to reduce this separation with the provision of suitable safety mitigations, such as barriers or screens.

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\(^{48}\) This type of protection is known in European standards as protection by clearance, but in this book “clearance” refers to air gap distances between two objects rather than between objects and people.
It should be noted that the term “live parts” includes the pantograph itself. Due to the position and width of the pantograph, this can often be the most extreme part of the live envelope; it is important to consider this in the OLE design for both clearances and separations through overbridges, stations, signals and other infrastructure. In the UK pantograph live parts are only permitted to breach the 3.5m separation distance if a site-specific risk assessment has determined that the safety risks have been mitigated.

9.10 Earthing and Bonding

At its simplest, traction bonding provides the negative half of the traction circuit, with OLE providing the positive half. However, this in itself is not sufficient to provide a safe system. *Traction earthing and bonding* is the collective term used to describe a set of arrangements designed to:

- Provide a low impedance path for traction current and fault current;
- Allow faults to be detected and cleared quickly;
- Keep the potential of exposed metalwork within safe limits\(^\text{50}\); and
- Eliminate touch potentials and step potentials.

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\(^{49}\) BS EN 50122-1:2011+A4:2017 Incorporating corrigenda November 2012 and May 2013 “Railway applications - Fixed installations - Electrical safety, earthing and the return circuit, Part 1: Protective provisions against electric shock”; 28 February 2017; BSI; figure 4

\(^{50}\) For 25kV AC systems in Europe, the voltage of exposed metalwork should not exceed 60V for any period >300s, and not exceed 645V for more than 200ms. Ibid.; table 4
Step potentials arise during fault conditions, or when current is allowed to flow to earth. During these conditions, the system earth electrode may be subject to a rise in potential. This will create a potential gradient in the surrounding ground, the potential reaching true earth or zero at some distance from the earth electrode. Step potential is the potential difference between a person’s feet caused by this potential gradient.

Figure 55: Step potential

Touch potentials arise where a metal service connected to another earth system (such as a level crossing barrier motor supplied from the DNO) is adjacent to OLE. In this situation, a person may be able to simultaneously touch the two earth systems (such as an OLE mast and an equipment cabinet). The two earths may be at different potentials, and so a current will flow through any person simultaneously touching both.

Figure 56: Touch potential
Both these situations give rise to unacceptable safety hazards, and so the earthing and bonding design must ensure these potentials are kept at acceptable levels.

9.10.1 AC Earthing and Bonding

AC systems are characterised by the creation of a distributed earth system using the general mass of earth; this is formed by using each OLE structure foundation as an earth connection. This system helps to keep the rail potential low in the event of a fault. The OLE structures are connected together by being bonded (along with earth wires) to the traction return rail, which may be one or both rails of each track (depending on the signalling system being used). This ensures that a fault on the structure will be cleared quickly. In electrical installation terms the earthing system is a TN-C type – that is, the Circuit Protective Conductor (CPC) and the neutral conductor functions are provided by a single shared set of conductors.

Other railway infrastructure is typically bonded to traction earth, to take account of the possibility that assets which lie within the OLE Zone and Pantograph Zone may become energised under OLE mechanical failure conditions. These faults will create a safety risk if not cleared quickly – in particular, signal structures and metal bridges are usually bonded to traction return. Additionally, OLE can induce unsafe voltages in adjacent metalwork without direct contact, as described in section 9.4. This particularly affects long continuous lengths of connected metal such as lineside fencing.

For these reasons all exposed metalwork within the equipotential zone are generally bonded to traction earth, to ensure that no dangerous potentials can arise.
An important factor governing AC bonding design in mainline railways is that the main function of the rail is often not traction bonding. The primary purpose is the guiding of trains, but it is also used by those signalling systems which use track circuits to detect the presence of a train. For these systems the track is electrically sectioned by means of Insulated Block Joints (IBJs), also known as Insulated Rail Joints (IRJs). A voltage is placed across the rails at one end of the track circuit, and a relay detects the voltage at the other end. A train axle shorts the circuit, and this shorting is detected and allows the signalling system to locate a train. Track circuits have their own bonding system, and so the traction bonding must be integrated with the signalling bonding. Track circuits which use IBJs are known as single rail track circuits; where these are used, one rail of each track is designated the traction return rail – (although confusingly it also carries track circuit current) and the other is reserved for signalling use only. Double rail track circuits (also known as jointless track circuits) eliminate the use of IBJs – which can pose reliability problems – by using high frequency AC voltages. For these types of track circuit both rails are used for signalling and traction currents, allowing the use of double rail traction return. Where no track circuits are present – in axle counter areas or sidings with no train detection – double rail traction return is also used.

AC railways use the traction return rails to form the core of the AC bonding system, and are typically configured to provide a path to earth of less than 1Ω impedance – this is known as traction earth. All of the conductors in the circuit – both live and earth – play a part in setting this

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51 Ibid.; figure 1. In this diagram the OLE Zone is marked OCLZ and the pantograph zone is marked CCZ
impedance, so any significant change to the OLE configuration will also have an impact on impedance and therefore protection settings (section 9.7.1).

Figure 58: Typical traction bonding for various track circuit scenarios. Note red and yellow bonds

The physical configuration of the bonding system is based on a set of simple principles.

**Traction rail continuity** must be provided at all locations, so that any train has a minimum of two paths for traction return current to flow; direct to the supply point, and in the opposite direction to the nearest cross bond location, and then back via another path. This is guaranteed by placing *continuity bonds* across any interruption in the traction return rail, such as *expansion joints* (where a gap in the rails is provided for thermal expansion).

Continuity must also be ensured where the traction return rail swaps sides, a situation frequently required in track circuited railways. In this case a *transposition bond* is placed across the IBJs which form the transposition point.

Figure 59: Transposition bond across IBJs (arrowed); Stratford, UK

Transposition bonds are also a necessary feature at turnouts in track circuited systems, where IBJs are necessary to prevent the turnout geometry from shorting out the two rails.
Low impedance is essential, and is attained by bonding the traction return rails together at frequent intervals. For instance, in the UK AC railways are provided with cross bonds which connect all traction return rails (and any earth wires) every 400m. These locations are coincident with DEPs (section 9.12.1) to provide a secure path to earth in the event of inadvertent re-energisation during an isolation.

Impedance is further reduced by connecting all of the OLE structures to the traction return rail, either directly or via an aerial earth wire. This provides two important features: firstly the foundations form a distributed earth farm, tying the whole system to earth potential; and secondly, it provides a direct connection for fault current on the event of an insulator or similar failure at a structure.

Figure 60: Cross bonding on axle counter railway; Newbury, UK

Jointless track circuits are prone to interference from traction fault current, so OLE systems which are co-located with this type of track circuit are provided with an OLE earth wire. This is connected to the traction return rail at cross bond locations by means of an impedance unit, which is a low-pass electrical filter that allows traction current to pass while blocking the track circuit frequency.

Figure 61: Structure to traction return rail bond; Harringay, UK

These are also provided at transposition bond locations. The OLE structures are then bonded to the earth wire rather than direct to the traction return rail. The earth wire may be buried, but is usually aerially suspended between structures for security.
Bonds are also provided at all feeding and sectioning points to connect the traction return rails and the neutral busbar at the feeder station, ATS or TSC. This forms the main path for traction return current to leave the rails, and as such these cables can give rise to dangerous voltages if disconnected. For this reason in the UK they are designated and marked as red bonds, meaning they should not be disconnected without an isolation.

Figure 62: Impedance unit forming transposition bond in TI21 jointless track circuit; Didcot, UK

Some bonds have a dual function, providing both traction continuity and track circuit continuity. These bonds are designated yellow bonds in the UK and marked as such.

All of these ground-level bonds are vulnerable to damage from track maintenance tamper vehicles, and regular inspections are required. In the UK spider plates are increasingly used to allow easy cable replacement.

Figure 63: Red bonds at a spider plate connecting a TSL to running rails; Acton, UK

These features collectively provide the backbone of traction bonding of any AC electrified railway. However this in itself does not provide a safe system since a large number of other assets and systems must also be protected. These include:

- Overbridges and underbridges;
- Station ironwork and metal canopies;
- Signalling structures;
- Level crossing barriers;
- CCTV and radio masts;
- LV power supplies for signalling, points heating, stations and level crossings;
- Metallic fencing;
- Crash barriers;
- Metal bridge parapets;
• Any other substantial exposed metalwork.

However it is often not desirable to connect LV equipment to traction return. For instance, LV equipment connected to a DNO earth will not tolerate OLE fault current; additionally, the two earth systems may be at different potentials, allowing current to flow between them.

**Figure 64: Structural reinforcing bonded to aerial earth wire; Farringdon, UK**

In this case, it is important to locate this equipment away from the OLE zone and a sufficient distance from traction bonded equipment that touch potentials may not arise. If this is not possible, an insulating shroud or earth gapping may be required instead.

Special considerations are needed at locations where flammable utilities are present, such as oil or gas pipes. It is often not safe to directly bond these items or to extend the equipotential zone to cover them, due to the risk of traction current flowing into the pipe.

Overline structures often have smaller electrical clearances (section 9.8) and so require special measures to mitigate the increased risk of flashover. In the UK non-metallic bridges with electrical clearances of less than Reinforced Insulation level are provided with *Conductive Assemblies* (also known as *Flashover Strips*). These copper strips are placed on the bridge underside in line with the OLE and bonded to traction earth. Any flashover will generally migrate to the conductive assembly as the lowest impedance path, resulting in the fault being detected and protecting the vulnerable concrete from arcing damage. Metallic bridges are bonded direct to traction earth and so do not need flashover strips.
For those items which are to be bonded to traction earth, the choice over how bond depends on the specifics of the system. Some administrations choose to nodal bond these items to traction return. This ensures that all fault current will flow along a well-defined single path to earth.

Alternatively the systems can be mesh bonded, providing multiple paths for fault current to flow. This has the advantage of reducing the fault impedance when compared to nodal bonding, but there is naturally less control over how much current flows in particular paths. Mesh bonding is particularly useful in station, where it can be difficult to separate traction and LV return systems.
Figure 68: Bond connections for a typical mesh-bonded railway
Sometimes structures need protection from AC traction current. In this case, secondary insulation may be used. This is an additional level of insulation inserted between the primary insulation and the mass of earth. A connection to traction return is made between the two sets of insulation, and this captures any fault current, preventing it reaching the general mass of earth.

![Secondary insulation diagram](image)

**Figure 69: Principal of secondary insulation**

This method is used to provide an additional level of protection against flashovers – for instance, at sensitive overbridge locations or heritage structures where AC stray currents are to be avoided.

![Secondary insulation photo](image)

**Figure 70: Secondary insulation protecting a sensitive viaduct; Kentish Town, UK. Note connection to earth wire (which is insulated from the structure)**

Special measures are required at the limits of electrified railways, to protect the adjacent non-electrified lines. This typically takes the form of single or double IBJs in all rails, to block any traction current from leaving the system.
9.10.2 DC Bonding and Stray Currents

Earthing and bonding principles for DC systems differ than those for AC systems. This is because DC stray currents can be especially damaging the running rails, as well as to metal services and foundation reinforcement – because of the phenomenon of cathodic corrosion (also known as galvanic corrosion). This occurs when current flows continuously between dissimilar materials – for instance from a metal into adjoining soil. The metal is corroded, eventually to such an extent that a hole may appear – a particular issue with metal services adjacent to the DC supply point. Stray currents will flow from the traction return rails into masts and foundations, and can corrode reinforcing bars, gas pipes and other metalwork.

![Figure 71](image)

Figure 71 (l-r): Foundation damage due to effects of stray currents on reinforcing bars, and replacement with secondary insulation to prevent DC current flowing into foundation (arrowed); North London, UK

These problems mean that on DC OLE the earthing system is entirely different to that of AC systems. The entire OLE system is insulated from the general mass of earth, so that stray currents cannot leave the system. DC tram systems typically use two levels of OLE insulation – double insulation\(^{52}\) – to protect people from electric shock and street-level assets from the effects of stray currents. OLE structures are not bonded to rails and so are protected from corrosion.

The lack of a system earth can lead to unacceptable voltages between the rails and exposed metalwork under high train load or fault conditions, and some systems counteract this by

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\(^{52}\) BS EN50122-2:2010 incorporating corrigenda February 2011 and March 2011 “Railway applications - Fixed installations - Electrical safety, earthing and the return circuit, Part 2: Provisions against the effects of stray currents caused by d.c. traction systems”; 31 March 2011; BSI
installing short circuit devices at passenger trains and substations to temporarily disconnect the supply.\textsuperscript{53}

![Image](image.png)

**Figure 72: Double insulation (red) on tram cantilever; Manchester, UK**

The question of how to insulate the return half of the circuit (the track) is more problematic; for a variety of reasons there is no one standard approach to this problem, but the available solutions can be grouped into three categories.\textsuperscript{54}

The first option – fully insulated earthing – provides insulation immediately below the rails, and bonds the rails to local earth at each substation. Thus the rails are intended to be the only path for return current. Maintenance of the rail insulation is essential to successful operation of this system.

In railways with a reinforced concrete trackbed, this system is often provided with a form of secondary protection – a stray current collection mat – in case of failure of the rail insulation. The steel reinforcing bars within the top layer of the trackbed are tied together to maximise its conductivity relative to the conductivity of those to ground. An additional parallel return cable may be bonded to the reinforcing bars to reduce resistance further. The reinforcement is typically

\textsuperscript{53} “Contact Lines for Electric Railways: Planning, Design, Implementation, Maintenance”, Kiessling, Puschmann, Schmieder, Schneider; 2\textsuperscript{nd} Edition, 2009 (revised reprint 2012); Siemens; p68

\textsuperscript{54} “Stray Current Control – An Overview of Options”, N. Dekker; 1999; IEE; Section 1
also connected to the substation earth. There some debate as to whether this secondary measure is effective at limiting stray current leakage. Older installations included a diode between the stray current collector and the substation earth, but this was found caused much higher secondary stray currents to flow, resulting in high levels of corrosion at the rail. As a result the use of diodes in this way is now deprecated in European Standards\textsuperscript{55}.

Figure 73: Fully insulated earthing and stray current collection mats on DC OLE

The second option – which is now being installed in many tram and metro systems – keeps the rails insulated but removes the earth connection at the substation, resulting in a \textit{floating return}. Theoretically this reduces the likelihood of earth leakage since no direct path to the substation is provided for stray current, but the disadvantage is that any stray current that does reach ground is no longer under control. Many systems use this in conjunction with a stray current collection mat.

The final option – one which has been widely adopted by historic DC systems – is to have no specific control means at all. Any rail insulation exists purely to reduce vibration and sleeper damage, and the electrical insulation properties are incidental. Some railways, such as the DC lines between London Euston and Watford, are able to operate satisfactorily in this way due to the geography and specifics of the feeding system\textsuperscript{56}, while others will experience ongoing corrosion problems due to the absence of mitigation methods.

\textsuperscript{55} BS EN50122-2:2010 incorporating corrigenda February 2011 and March 2011 “Railway applications - Fixed installations - Electrical safety, earthing and the return circuit, Part 2: Provisions against the effects of stray currents caused by d.c. traction systems”; 31 March 2011; BSI; section 8

\textsuperscript{56} “Stray Direct Current – a View from the Main Line”, F. Waterland; 1999; IEE; section 2
9.11 Dual Voltage Areas

There are many locations where AC and DC electric railways meet, including:

- AC and DC systems coming into proximity at a complex location, such as a tram-train interchange;
- Separate AC and DC railways running in parallel on a transport corridor or at a station;
- Separate AC and DC railways crossing, either at grade, overline or underline;
- Voltage conversion within a single railway, with trains switching from AC to DC and vice versa at a voltage switching location;
- A single railway carrying both AC and DC electrification in parallel – usually meaning AC OLE and DC 3rd or 4th rail.

We have seen that the bonding arrangements for AC and DC electrification are in opposition to each other, and this poses special problems whenever the systems meet. While in theory each system can affect the other in undesirable ways, in practice – and often depending on the standards applied when the first system was built – one system can usually be considered the cause and the other the victim\(^\text{57}\). The level of interference is largely determined by the

\(^{57}\) “Consequences of DC Components in AC Railway and their Elimination”, Midya, Thottappillil, Schütte; 2007; Uppsala University
configuration of the traction systems involved, which adds another level of complexity. AC systems will produce interference via inductive coupling, and to a much lesser extent can also interfere via capacitive coupling; meanwhile DC systems will typically export cathodic corrosion to surrounding systems. Problems can multiply when the signalling systems of the respective systems are included – immunisation against AC being no protection against DC, and vice versa.

The particular geometries of the interaction play a part in determining the effects, and make modelling of the problem much harder. There is no single perfect solution to the interaction of AC and DC systems – each situation must be assessed and modelled, and an appropriate solution found. All of the available solutions involve compromises, and are best described as controlling the problem, rather than eliminating it. It is much harder to design immunisation problems out of a system after it is built, and so wherever possible the solutions should be incorporated during the original construction.

A full description of the potential solutions is beyond the scope of this book, but the following sections describe solutions which have been used to greater or lesser effect, and their respective advantages and disadvantages. A list of UK locations with dual voltage electrification, and their mitigation measures, can be found in Appendix B.

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58 “Stray Direct Current – a View from the Main Line”, F. Waterland; 1999; IEE
9.11.1 AC/DC Transition - Isolating Section in AC

This solution is relevant at a transition between an AC and a DC system on a single set of tracks. Here the requirement is to permit changeover from AC to DC and vice versa, allowing for continuous operation of trains; while protecting vulnerable lineside LV systems and OLE structures from the effects of stray currents. IBJs (section 9.10.1) are used to prevent the flow of DC current from the rails into an AC area, or vice versa. It is necessary to provide two sets of IBJs, sufficiently far apart that the longest train (electric or otherwise) cannot bridge both sets; otherwise each train would connect AC and DC areas together, and undesirable currents would flow through the train body.60

However this arrangement still requires a means to be provided for traction current to return from an electric train to the power supply. The means of doing this depends on the specifics of the interfacing electrification systems.

![Figure 76: Isolating transformers at boundary of 3rd rail DC and overhead AC area; Acton, UK](image)

The first option places the isolating section in the AC-only railway. Section insulators (section 10.7.1) are placed directly over the IBJs, and isolating transformers (1:1 current transformers) are used to transmit power to an AC train beyond the IBJs. The OLE earth wire is segregated and all OLE structures bonded to the adjacent earth wire section. The system is analogous to an airlock, 

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60 Ibid.; Appendix A
allowing continuity of AC traction current to the train but blocking DC current, which cannot flow across the transformer interface.

The following diagrams depict transfer from an AC OLE system to a DC conductor rail system, but these methods can equally be applied to AC OLE to DC OLE transfer, when combined with a suitable neutral section (section 10.7.3).

![Diagram of Isolating Transformers Used for AC/DC Isolating Section](image)

**Figure 77: Isolating transformers used for AC/DC isolating section**

This option has the advantage of being simple, with no moving parts or control system required. However care is needed in the design of earthing and bonding to ensure that the OLE structures and bonding does not provide a path for current to bypass the isolating transformer. For this reason, complex track layouts, station areas and overbridge locations are best avoided.

![Diagram of Resistors Used for AC/DC Isolating Section](image)

**Figure 78: Resistors used for AC/DC isolating section**

A simplified version of this configuration removes the section insulators and provides continuous OLE into the isolating section, and then connects resistors across the IBJs, with a resistance value that ensures the volt drop does not cause electric shock risk or damage to trains. This reduces stray
currents rather than eliminating them, but can work if DC voltages, AC traction currents and AC fault currents are all low.

A further variation replaces the resistors with *bandpass filters* – consisting of capacitors and inductors – which block DC current but allow the AC traction frequency current to flow unimpeded. *Spark gaps* are provided to protect the capacitors in the event of a short circuit. This solution needs very careful design, since ageing of the filters, harmonics and over-voltages can all damage the equipment or cause unsafe voltages to arise.

### 9.11.2 AC/DC Transition - Isolating Section in DC

Alternatively, where an AC OLE railway interfaces with DC conductor rail, the isolating section can be placed in the DC system. The two sets of IBJs are retained, and the conductor rails are gapped coincident with the IBJs. *DC contactors* are used to temporarily bypass the gaps and IBJs when trains are passing. The contactor operation is triggered by the train detection system, and is configured so that the contactors at each end of the isolating section are never closed simultaneously. It thus provides a similar airlock approach to that of section 9.11.1, but by mechanical rather than electrical means.

![Figure 79: DC contactors used for AC/DC isolating section](image)

This system is effective, but adds complexity and significant maintenance of the contactors and control equipment. Stray current monitoring is typically provided for this configuration.

### 9.11.3 Shared AC and DC Lines

Lines which are provided with both AC and DC electrification on a single set of tracks – usually AC OLE and DC 3rd or 4th rail – present a particular problem since the segregation methods outlined in previous sections cannot be used. The principles of AC bonding (section 9.10.1) are
completely at odds with normal provisions to prevent DC stray currents from flowing in other metallic systems, whether it be the OLE itself, an LV station supply or a steel bridge.

A number of different approaches are available, which may be more or less effective depending on the specifics of the situation:

- **AC bonding principles are maintained as per section 9.10.1, and special measures are taken to limit the magnitude of DC stray currents.** This could include a DC substation which only feeds the dual voltage area, with conductor rails and running rails isolated from the remaining railway; reducing the volt drop in the DC return circuit, using parallel return cables or additional rails in the return circuit to reduce the resistance; and bonding railway metalwork such as station and bridge metalwork to traction return as close to the DC substation as possible;

- **AC bonding principles are maintained as per section 9.10.1, and special measures are taken to limit the impact of DC stray currents.** This could include reinforcement of bonding conductors and earth wires; a specially-designed DC substation at the AC/DC changeover point to keep DC rail voltage at zero or a negative value; and segregation of earths of third party assets from the rails;

- **Devices such as spark gaps or non-linear resistors placed between bridge and station metalwork and the traction earth; these prevent DC from flowing into the asset, but allow AC fault current to flow across the device.** These devices are not trouble-free; spark gaps can weld themselves closed, and non-linear resistors are hard to use in high fault current situations.
9.12 Earthing for Construction and Maintenance

9.12.1 Temporary Earthing Arrangements

Temporary earths are required to protect staff against inadvertent re-energisation during construction and maintenance. These earths are connected between the OLE and the earthed structure at a Designated Earth Point (DEP). Earthing stalks and/or line guards are provided on the OLE for these connections, which are coincident with cross bonds (section 9.10.1) to ensure a secure path to earth for fault current.

Figure 80: Line guard (arrowed) for applying portable earth to catenary; Birmingham, UK

In the UK, construction earths (blue) are differentiated from maintenance earths (orange).

Figure 81: Designated Earth Point with portable construction earths (arrowed) applied
9.12.2 Buffer Sections and Permanent Earths

It is often necessary, for the protection of staff during a longer period of OLE construction works, to permanently earth a section of OLE using a *Permanent Earthing Section* (PES). This is done by isolating the section of OLE from the live sections around it, and installing permanent earths at the limits of the section. Construction earths close to the start of the PES then form the *safe limits of work* for construction staff.

![Diagram of Permanent Earthing Sections](image)

**Figure 82: Principles of permanent earthing and buffer sections**

![Image of Permanent Earthing Connections](image)

**Figure 83: Permanent earthing connections; Newbury, UK**
10. Mechanical Principles

10.1 The Pantograph

The key interface to be considered in OLE design that of the contact wire and *pantograph* (or *pan*). It is the pantograph which collects traction current from the OLE, and it is so-called because of the parallel linkage used to maintain a level pantograph head.

![Typical pantograph; Paddington, UK](image)

This linkage ensures the head is always parallel with the contact wire. The pantograph is maintained on the wire by an upward force generated by an actuator (which is generally a pneumatic cylinder, although historically has been a mechanical spring). This raises the lower arm, and the upper arm is raised either by an external bar linkage, or by an internal 4th bar which pulls a set of chains around a cam at the *knuckle*. This approach has the advantage of minimising aerodynamic disturbance from external links. The actuator also acts as the *primary suspension* for the system. *Secondary suspension* is usually provided on pantograph heads designed for mainline railways, and some high speed pans provide *tertiary suspension*. Secondary and tertiary suspension can be provided by a variety of means, from torsion bars to radial arms or plunger springs.
The head itself is designed to be of low mass to reduce inertia, and typically supports one or more rows of carbon strips\(^{61}\); these form the interface with the contact wire. Carbon is used because it has good electrical and thermal conductivity, is self-lubricating, and has a much lower hardness than the contact wire. This means that most of the frictional wear is taken by the carbon strips rather than the OLE (it being far easier and cheaper to replace the carbons than the contact wire). Many administrations, including the UK, impregnate the carbons with copper (and historically, lead) flakes to improve its conductivity. In the UK up to 35% impregnation by weight is permitted.\(^{62}\) A set of carbon strips will typically last 80,000km before needing replacement.

In many mainline and high speed pantographs the carbons are glued into an air channel, which is connected to a compressed air circuit. In the event of loss or excessive wear of a carbon strip, air pressure is lost and the pantograph *Auto-Drop Device* (ADD) lowers the pantograph, thus reducing the chances of damage to the OLE. Modern pans have a fast-drop capability to further reduce the risk of damage.

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\(^{61}\) Some low speed pantograph designs use a metallic strip instead.

\(^{62}\) NR-L2-ELP-27715 “Overhead Contact System Design Specification Module 1: Fundamental Design Requirements”; Issue 1, March 2018; Network Rail; section 7.3.1
All pantographs have a specified operating range; that is, the vertical distance over which they will safely operate, with a mechanical behaviour that is broadly the same. Pans with an auto-drop mechanism will generally also retract if the pantograph exceeds the upper operating limit.

The pantograph to contact wire interface is a complex one, comprising as it does three interacting dynamic systems (the pantograph, the OLE, and the train) each with various modes of movement.

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63 BS EN 50367:2012+A1:2016 Incorporating corrigenda June 2012 and August 2013 “Railway applications – Current collection systems – Technical criteria for the interaction between pantograph and overhead line (to achieve free access)”; 31 March 2017; BSI; figures A.6 and B.6
The pantograph itself can be approximately modelled as a spring-mass-damper system. In simple terms, the pantograph is arranged to exert an upward force on the contact wire - the contact force. This is ideally a constant force, but several factors prevent this in practise. Aerodynamic effects on the pantograph are different depending on speed and whether the pantograph is knuckle leading or trailing. This can be partially overcome on modern pans by means of tuned aerofoils on the knuckle and/or head, and/or tabs on the horns to counteract the aerodynamic lever effect on the head.

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64 “Lump Mass Models for Legacy Pantographs on GB Mainline”, Conway; November 2016; Current Collection Solutions/RSSB; p7
The contact force also varies somewhat with wire height, due to the mechanical arrangement of the pantograph linkage and actuator. Additionally, the friction of the knuckle itself can lead to varying force (hysteresis) depending on whether the pantograph is rising or falling.

In Europe the design of pantograph-OLE interface is governed by the Technical Standards for Interoperability (TSIs), as transposed into European Standards, and these specify that a compliant AC OLE/pantograph system for up to 200kph linespeed will have a contact force distribution such that the mean contact force ±3σ (3 standard deviations) is always between 0 and 300N. Static contact force is generally set at 70N or 90N at the pantograph. As dynamic contact force is added, higher forces will be seen at discrete features, and forces up to around 350N can be accommodated without risk of damage.

Pantographs at the front of a train experience higher levels of air turbulence, due to the nose of the train pushing air around it. Airflow at the rear of the train tends to be smoother, so many administrations run their medium and high speed services using the pantograph at the rear of the train.

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65 On high speed systems, this problem is overcome by providing OLE at a constant contact wire height.
66 BS EN 50119:2009+A1:2013 “Railway Applications – Fixed Installations – Electric Traction Overhead Contact Lines”; 31 May 2013; BSI; section 5.2.5.2
train set, with the front one out of use in normal operation. This has the added advantage that in the event of a dewirement, the events will generally occur behind the front pantograph, leaving it undamaged and able to power the train after an incident.

### 10.1.1 Types of Pantograph

The UK currently has 11 different types of pantograph in active use; six on the mainline, 2 tram/metro types, and 3 which are confined to High Speed One (section 8.5). A full list can be found in Appendix C.

Early pantographs used a diamond linkage configuration (see Figure 5 for an example), and later the cross-arm type was adopted; but a more sophisticated mechanical linkage design allowed parallelism to be maintained with a more responsive single arm\(^{67}\). In the UK this began to overtake the cross-arm design when the Stone-Faiveley AM/BR pantograph was introduced in 1959.

British Rail subsequently went into partnership with Brecknell Willis to develop a new single arm pantograph which would (after several iterations) be capable of reliable operation at speeds of 225kph. The resulting *Brecknell Willis High Speed* pantograph became the template for most mainline railway pans in the UK\(^{68}\), which all conform to the BR head profile shown in section 10.1.

The exception is on High Speed One, where a series of Faiveley high speed pans are used. These are matched to the French pattern OLE system on that route, having previously been used on TGV trains (section 7.4). HS1 pans use a different geometry with insulated horns, and have different dynamic characteristics. For this reason the HS1 pantographs are not permitted to run on UK conventional routes.

For the lower speeds of tram and metro systems it is not necessary to have the sophistication of secondary suspension or aerodynamic balancing, and so simpler pantograph designs are used.

Engineering development is now focused on active pantographs, where the contact force is measured many times a second and fed back to a controller which varies the actuator force. The Faiveley CX pantograph used in the 2007 speed record used this principle.

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\(^{67}\) Invented by Louis Faiveley in 1955

\(^{68}\) For more information on the development of the BWHS pan visit Dave Coxon’s train testing site at [www.old-dalby.com/HSCCP.htm](http://www.old-dalby.com/HSCCP.htm)
10.1.2 The Pantograph-OLE Interface

The contact force from the pantograph creates a vertical displacement on the contact wire – uplift. When the train is moving this uplift combined with the along track movement creates a mechanical wave in the contact wire. In simplified terms the pantograph can lose contact with the wire if the train catches up with the wave it creates. Since the speed of the wave is proportional to the square root of the wire tension, the OLE system designer will set the contact wire tension so that wave speed > 1.4 x maximum train speed. For higher speed systems this increased mechanical tension becomes a key constraint on the selection of conductors (section 10.17) and control of mechanical forces in line fittings (section 10.18.1) and OLE supports (section 10.15). Actual performance is however much more complex, due to higher order wave harmonics. These are affected by parameters such as presag (section 10.2), dropper spacing and discrete features in the wire.

A key factor in the system performance is the elasticity (measured as uplift per unit of contact force) of the OLE. Ideally this would be uniform throughout the system – however in reality the elasticity is less at the OLE structure, due to the support arrangement on the catenary restraining the system, than at the midspan between structures.

Therefore the OLE system designer will match the elasticity differential in the system to the performance requirements. The higher the linespeed, the lower the required elasticity differentials. See section 10.2 for details.

For high speed systems, the absolute elasticity must also be controlled, to counteract the increased dynamic contact force and keep uplifts within the available movement of the OLE. A typical high speed system has a maximum uplift capability – the design uplift – of 200mm. This means actual uplifts should be no greater than 100mm.

Trains with multiple pantographs pose a further problem; the wave travelling backwards from the front pantograph can interfere with current collection at the rear pantograph. OLE systems designed to run with multiple pantographs at high speed therefore require particular care in the selection of tension and droppering.
A further problem is that of hard spots; any component attached to the contact wire - such as a dropper clip (section 10.17.4) or registration arm (section 10.14.2) – reduces the elasticity locally, and each hard spot will reflect a portion of the wave back towards the train. Excessive hard spots will lead to loss of contact at the pantograph, and can cause damage to the carbons which then create a vicious circle of OLE/pantograph damage.

Conversely, an over-tensioned z-dropper (section 10.11.11) can lead to hogging which will also affect dynamic performance.
Heating effects can be significant at the pantograph/contact wire interface – a particular issue when the train is stationary and aerodynamic cooling is not available. For this reason trains may have limitations on their power consumption when at rest.

The contact area must be set according to current requirements, and DC pantographs (needing higher currents) have either a larger contact area with multiple carbon strips, or use multiple pans.

Figure 91: Loss of contact and arcing caused by poorly adjusted dropper

Figure 92: Brecknell Willis DC pantograph with four carbon strips
10.2 Suspension Arrangements

Various suspension systems have been developed for the different performance requirements of OLE.

At its simplest, OLE can consist of a contact wire suspended directly from support structures. This is known as tramway or trolley OLE.

![Figure 93: Tramway OLE](image)

Although simplest in terms of engineering, the elasticity is zero at the support point and very high at the midspan; and since there is no support to the contact wire between structures, spans are typically limited to 40m. For these reasons, it is suited only to very low speed (≤ 30kph) lines for tram networks and heavy rail sidings.

The tram system can be improved by the addition of a stitch (also known as a bridle). Here the support is transferred to the stitch wire, which in turn suspends the contact wire. The length of stitch may be varied for the particular system.

![Figure 94: Stitched tramway OLE](image)

The stitch creates some elasticity at the support, and this type of suspension is often used on tram systems, giving good current collection up to 80kph.
The next step is to create a suspension wire running the whole length of the system. This is the *simple catenary* system – so called because a wire suspended in space describes a catenary curve\(^\text{69}\) under gravity. The contact wire is suspended from the catenary by vertical droppers.

![Figure 95: Simple catenary OLE](image)

This system gives better elasticity at the support and is the simplest system adequate for mainline railways. For this reason it is widely used around the world, and gives good current collection up to 120kph. It also provides the additional cross section necessary for delivering increased traction current.

Above this speed there are three options available. The first option modifies simple equipment to use a *presagged* contact wire. Rather than keeping the contact wire flat across the span, a deliberate amount of *sag* is introduced between the first and last droppers – typically of 1/1000 of the *span length* (the distance between structures).

![Figure 96: Presagged simple catenary OLE](image)

The purpose of the presag is to compensate for the greater elasticity at the midspan, since the uplifted contact wire position at midspan is closer to the uplifted position at the support. This system has found favour in the UK and France, and works at all speeds – this system powered the current rail world speed record holder (section 6.1).

It is also possible to introduce a stitch wire into simple catenary. The tension in the stitch can be set so as to reduce the elasticity even further.

\(^{69}\) Technically a suspend wire describes a *cosh curve* rather than a true catenary, but the differences are very small.
This system is favoured on high speed lines in Germany, where it is used for speeds up to 300kph. Some German stitched systems also have presag\textsuperscript{70}. The UK trialled stitched equipment in the late 1950s, but it was subsequently removed on all but the Brown Boveri system (section 12.1.5).

A further development is the introduction of a third wire – the \textit{auxiliary catenary}. This gives us the \textit{compound catenary} system.

This also gives very low elasticity variation, and many of the first mainline systems in the UK were compound. It has since fallen out of favour in the UK due to the complexity and maintenance requirements. Elsewhere in the world it is still widely used, notably in Japan, where the Shinkansen lines (section 7.4) make extensive use of compound equipment at speeds up to 300kph.

10.3 Tensioning Arrangements

OLE must be tensioned to maintain the contact wire height under gravity. Contact wire tensions run from 8kN for slow speed systems, right up to 40kN (used for the world speed record attempt). Typically, mainline systems run between 10 and 20kN.

The tensioning arrangements must take account of the expansion and contraction of the wires with varying temperature. Each system has a defined \textit{temperature operating range}, and a complete length

\textsuperscript{70} “Contact Lines for Electric Railways: Planning, Design, Implementation, Maintenance”, Kiessling, Puschmann, Schmieder, Schneider\textsuperscript{2nd} Edition, 2009 (revised reprint 2012); Siemens; p160
of OLE (or wire run) will expand and contract as much as 1.5 metres over a typical range\textsuperscript{71}. This has a major effect on tensioning arrangements.

The simplest system is known as Fixed Termination (FT). Here the catenary is fixed and tensioned at every structure. The contact wire is tensioned at each end, and allowed to expand and contract in between, but is restrained by the droppers attached to the catenary.

![Fixed termination OLE](image)

**Figure 99: Fixed termination OLE**

As temperature increases, the contact wire will sag between structures. As it decreases, the contact wire will hog. This change in profile will affect the system dynamics; for this reason, FT systems are not suited for higher speeds, and are generally only used on tram and sidings systems.

Care must be taken when designing FT systems to ensure that all fittings can withstand the maximum tension in the system.

![Fixed termination portal cantilevers; Euston, UK](image)

**Figure 100: Fixed termination portal cantilevers; Euston, UK**

FT cantilevers are configured to pivot in the vertical plane, so that tension changes do not stress the cantilever frame, while using the frame weight to prevent large tension differences between spans.

The standard system for medium and high speeds is the Auto Tensioned (AT) system. Here the catenary is fixed only in the centre of the wire run at the midpoint anchor; the whole system is free

\textsuperscript{71} For instance, modern UK mainline systems are designed to operate in an ambient air temperature of \(-18°C\) to \(+40°C\)
to move around this fixed point. Constant tension is provided by a tensioning device – traditionally by a set of balance weights attached to the catenary and contact wire.

Mechanical advantage of 3:1 – or for higher tensions, 5:1 – reduces the size of the weight stack required, and is provided via pulleys or drumwheels. The weights travel up and down the mast as the system expands and contracts. A single set of weights can tension both contact wire and catenary, but modern mainline and high speed systems typically have independent tensioning of the two wires.

**Figure 101: 3:1 ratio pulley type balance weight anchors; Winson Green, UK**

Balance weights are a significant hazard in the event of a dewirement – without a means of stopping the fall of the weights, they can be a hazard to staff and to passing trains, and (for independently tensioned systems) cause further OLE damage via dropper breakage.

**Figure 102: Siemens drum type anti-fall balance weight assembly; Rugby, UK. Point of engagement of anti-fall wheel with stop arrowed**

For this reason modern balance weight assemblies use a drumwheel which includes an anti-fall mechanism; usually a simple toothed wheel which engages with a ratchet stop in the event that tension is lost. This prevents further fall of the weight stack. Balance weights on tram systems are usually configured to travel inside the support mast to avoid these issues and prevent vandalism.

Balance weights are simple and robust, but for mainline railways where reliability is critical and maintenance access limited, they suffer from a number of disadvantages. The need for vertical travel means they must be placed on a mast, and for multi-track railways this means the OLE on inner tracks must be routed out to the mast; either using a set of right angle pulleys at a portal, or by threading the wire run directly through the outer track OLE to the mast. The former system introduces complexity and failure modes, and the latter means that wire runs are interconnected
and no longer have mechanical independence. Weight theft can also be an issue when metals prices are high.

A recent development is the use of spring tensioners instead of balance weights. These maintain a constant tension by using a mechanical spring. Since a spring applies a force in accordance with the equation $F = kx$, the tension would ordinarily vary with the spring extension.

Figure 103: 5:1 ratio pulley type balance weight anchor for high speed equipment; Stratford, UK

To eliminate this, a shaped cam is used to provide a constant force. The tensioners are often placed over the track for ease of maintenance access using rail-mounted plant. Spring tensioners come in varieties which use a helical spring, and a more compact arrangement using a spiral torsion spring.
All tensioners have an efficiency of less than 100%, caused by the friction within the tensioner mechanism. Tensioner efficiency should be at least 97% for good performance.

Whatever tensioning device is used, along track movement is provided for at intermediate structures by pulleys, flexible links or pivoted cantilevers. Only the catenary supports closest to the midpoint anchor can be directly clamped. The tension is not entirely constant, varying slightly due to the drag caused by cantilevers pivoting the wire away from the neutral temperature position. However with good design, the tension variation can be kept below 3%. Cantilevers in AT systems pivot in the horizontal plane so as not to unduly influence the contact wire profile, and so it is important to limit stagger change as the rotation of the cantilever moves the wire away from its design position.
Other tensioning devices are sometimes substituted, such as gas systems where space is restricted. These have the disadvantage that their travel is proportional to the change in gas pressure, and therefore ambient temperature rather than wire temperature (which can be significantly higher or lower). They cannot therefore provide a constant wire tension.

Some administrations, including the UK, have experimented with hybrid systems, with auto-tensioned catenary and fixed termination contact wire, or vice versa. These arrangements were shown not to provide good performance and are not used in modern systems.

10.4 Tension Lengths and Overlaps

The length of a wire run is limited\(^\text{72}\) due to the maximum drag and stagger change requirements detailed above – as well as practical considerations such as maximum wire length on the wire drum. OLE is therefore split into tension lengths (also known as wire runs). Turnouts and crossovers are provided with their own wiring (section 10.5), and due to the shorter length of OLE needed are often provided with a half tension length comprising a tensioner (section 10.3) at one end, a fixed anchor (10.11.10) at the other, and no midpoint anchor (section 10.11.11).

At the end of each tension length (or half tension length) arrangements must be made to transfer the pantograph from one tension length to the next. This transfer arrangement is known as an overlap. At its simplest, an overlap is a purely mechanical arrangement. However, it is also a convenient place to create an electrical break in the OLE for sectioning purposes.

\(^{72}\) For example, UK mainline systems have length limits varying from 1500m to 1970m
The overlap type is defined by two parameters; the number of spans of parallel running; and whether it is uninsulated (also known as a construction overlap) or insulated.

An insulated overlap takes advantage of the fact that each wire run has a zone where it is out of running (not in contact with the pantograph). At this point insulation can be inserted in each wire without the complication of an in running type insulator. An isolator (section 10.8) or booster transformer (section 9.4.2) may then be connected around the electrical break.

It is important when configuring overlaps to ensure that electrical continuity is provided (through uninsulated overlaps) and that all wire run sections are at the same electrical potential (for insulated overlaps). This is achieved by applying flexible jumpers between wire runs. For electrical continuity current carrying jumpers are used, and these are generally duplicated to provide redundancy. For voltage equalisation equipotential jumpers are used.

A third type of jumper, the C-jumper, is used to provide current sharing between contact wire and catenary in systems which do not have current carrying droppers (section 10.17.4).

It should be noted that, when used as an electrical break for a booster transformer, a train brought to a stand in the overlap will short out the booster transformer. This can lead to arcing and contact wire burnout, and for this reason overlaps are placed carefully relative to signals.

### 10.4.1 Zero Span Overlap

The simplest form of overlap is the zero span. This has a single point transfer, with no spans of parallel running.
Figure 110: Uninsulated zero span overlap

The zero span arrangement is only suitable for low speeds on tram and siding systems, due to the relatively hard spot and short length of the transfer zone.

10.4.2 Single Span Overlap - Conventional

Higher speeds are achievable using a single span overlap. This has a single span of parallel running. The pantograph is transferred gradually from one wire run to the other; within the parallel running section, it is in contact with both. The out of running contact wire is set 300-500mm above the in-running wire at the structures depending on the system parameters.

Figure 111: Uninsulated single span overlap

Figure 112: Insulated single span overlap
The single span overlap is used worldwide, and is the standard for UK heavy rail up to 200kph. To confuse matters, many reference sources refer to this arrangement as a three span overlap.

### 10.4.3 Single Span Overlap – Without Anchor Spans

A recent development in the UK is to remove the anchor spans from the single span overlap and terminate each wire run at the end of the overlap span. Without careful design this would result in poor pantograph dynamics, but it is possible to adopt a very specific vertical profile, using the natural rise or circumflex of the contact wire to ensure good parallel running. A pulley is mounted below the spring tensioner (section 10.3) to ensure that the height of the terminating contact wire remains constant. This arrangement has been proven for speeds up to 200kph.

![Figure 113: Series 1 single span overlap configuration](image)

![Figure 114: Series 1 single span overlap anchor with underslung pulley; Swindon, UK](image)
10.4.4 Multiple Span Overlaps

For higher speeds, the increased elasticity variation created by the wire being lifted out of running, and waves being reflected back from the anchor (section 10.11.10), become barriers to good current collection. Therefore the number of spans of parallel running is increased. High speed OLE typically uses two span overlaps.

**Figure 115: Uninsulated two span overlap**

**Figure 116: Insulated two span overlap**

This system is used on European high speed lines at up to 300kph. Some high speed lines use three, five or even seven span overlaps.

10.5 Turnout and Crossover Wiring

Special arrangements are required where tracks diverge or converge, to ensure continuity of current collection and minimise dewirement risk. At the core of this arrangement is the control structure; an OLE structure placed at a specific point in relation to the turnout. System requirements vary, with some systems needing a toe opening (separation between the rails) of between 150mm and 300mm, and others 200mm to 350mm.

10.5.1 Low Speed Tangential Method

The simplest way to wire a turnout is to use an additional wire run for the turnout, with no connection between the two wire runs and pantograph transfer at the control structure.
This is satisfactory for low speeds, and is used extensively on trams systems and in heavy rail sidings. However as speed rises so does the uplift; and this leads to the situation where the wire run carrying the pantograph rises, but the other wire run does not, leading to the risk of hookover.

10.5.2 Cross Contact Method

One method used to minimise the hookover risk is to use a cross contact arrangement. In this case the two wire runs cross, and a cross contact bar is provided at the contact wire crossing point, which is set inboard of the control structure by careful staggering. The cross contact bar ties the two wires together – the mainline wire is placed below the crossover wire – while allowing for along-track movement. This ensures that the wire run which is not in contact with the pantograph follows the lifted wire, so that hookover risk is minimised.
The cross contact system has been used extensively in UK heavy rail, although the cross contact bar can cause a hard spot if poorly designed, leading to fatigue of the bar. For this reason use in the UK is now limited to speeds below 160kph or where there is no practical alternative. Cross contact has however been successfully used in Europe with a specially-designed lightweight T-shaped cross contact bar and appropriate droppering.

Figure 120: Cross contact bar (clockwise from top left): general arrangement; traditional installation at Rugby, UK; Siemens T-bar detail

10.5.3 Cross-Droppered Method

In addition to the cross contact method, some systems also use cross droppering. This entails droppering the mainline catenary to the crossover contact wire in the vicinity of the cross contact bar, to spread the lifting effect of the cross contact over a longer length. This system has been used in recent UK turnout wiring at speeds up to 200kph.

Figure 121: Cross-droppering arrangement viewed from below; Swindon, UK
10.5.4 High Speed Tangential Methods

Modern UK systems have moved away from the cross contact arrangement for the reasons given above, and instead adopted a more sophisticated form of tangential arrangement.

The first system to do so was UK1 (section 12.2.7), used for the West Coast Route Modernisation. This uses a specific dropping arrangement and a span where the two wire runs are in parallel on the lead up to the control structure, to ensure that the pantograph picks up the crossover wire run without hookover risk.

Figure 122: UK1 tangential wiring (diverging route behind photographer); Ledburn Junction, UK

Figure 123: UK1 tangential wiring - profile view showing double dropper

This system, though effective, was felt to be overly-complex and hard to set up and maintain. For this reason, the latest Series 1 (section 12.3.4), Series 2 (section 12.3.3) and UK Master Series designs instead use a simple tangential arrangement with one, or preferably two, spans of parallel OLE before the control structure, and cross-dropper at the turnout.
10.5.5  High Speed Three Wire System

All the systems described so far use a single wire run on the crossover itself. Since the running lines generally have separate electrical sections (section 9.3), this means a section insulator (section 10.7.1) is required on the crossover. Some high speed routes have high speed turnouts, where the dynamic performance of a section insulator would be unacceptable.

They therefore use two wire runs on the crossover, allowing the use of an insulated overlap (section 10.4.2) on the crossover to achieve the necessary section break.
This means that a *triple cantilever* is needed at the control structure, and transfer is achieved by careful positioning of the three wires. This arrangement is not common in the UK, but is used on High Speed One.

### 10.6 Overlaps in Multi-track Areas

Wiring of overlaps and crossovers becomes more complex in multi-track areas, particularly on systems which exclusively use tensioners on masts; it becomes necessary to extend the conductors on inner tracks through those on the outer tracks to reach a mast. This is most easily done by merging the wire run conductors into a single wire, known as a *tail wire*. This is done using an equalising plate (section 10.18.1) and allows the wire run to pass between the catenary and contact wire of the outer track(s).

![Figure 126: Tail wire (shaded red); Peterborough, UK](image)

### 10.7 Other Electrical Break Devices

#### 10.7.1 Section Insulator

Although overlaps are used wherever possible to create section breaks, there are times when additional breaks are required for switching and sectioning. At these locations, a *Section Insulator* (SI) is used. This is a set of insulators spliced into the contact wire and catenary, while allowing the pantograph to pass over it. A standard insulator is used in the catenary, and an arrangement of
insulators and skids are placed in the contact wire; this allows the pantograph to pass over it without loss of current collection.

![Figure 127: Plan view of typical SI](image)

SIs are a significant hard spot in OLE, and for this reason their use is generally restricted to crossovers, sidings and station areas where speeds are lower. They should be supported at a structure wherever possible – if not, the droppers must be shortened locally to counteract the dead weight of the assembly. SIs are also difficult to set up, and there are more restrictive rules on horizontal position, depending on the width of the SI.

### 10.7.2 Insulated Knuckles

Many historical systems have achieved electrical separation of adjacent wires in complex track layouts using an *insulated knuckle*. This takes the form of one or two insulators directly attached between two wire runs. Although electrically effective, the large and often unsupported mass means dynamic performance and contact wire wear is degraded. These assemblies are not used in modern systems.
10.7.3 Neutral Sections

An electrical break is required wherever different supply phases meet (section 9.1.3); or where there is a change of system voltage, as occurs at many European interfaces; or where an earthed section of operational OLE is to be provided at a location where sufficient electrical clearance (section 9.8) cannot be provided. At these locations a neutral section is used. This is a section of earthed OLE sandwiched between an insulator either side. For AC systems fed from three phases with a phase angle of 120°, the total strength of the insulation between phases must be $\sqrt{3} \times$ line voltage\(^{73}\).

Neutral Sections are found at feeder stations and midpoint sectioning locations (section 9.1.3). The train must not draw power through the neutral section, since an arc would be drawn to earth. For this reason the train power is tripped off by a trackside Automatic Power Controller (APC) magnet, which operates the train’s circuit breaker via a relay.

\(^{73}\) It is possible to reduce this potential difference somewhat by using specific patterns of 3 phase connections, as has been done on the Madrid-Seville line. “Contact Lines for Electric Railways: Planning, Design, Implementation, Maintenance”, Kiessling, Puschmann, Schmieder, Schneider\(^{2}\) Edition, 2009 (revised reprint 2012); Siemens; p42
When the train has cleared the neutral section, the circuit breaker is closed by a second APC magnet. For this reason care must be taken to place signals so that there is no risk of a train becoming stranded at a neutral section.

There are two types of neutral section; the inline type, and the overlap or carrier wire (CWNS) type.

The inline type consists either of glass bead insulators (over which a pantograph is able to run), or high speed section insulators, placed either side of the neutral point. Sacrificial arcing horns are often provided in the event that a train draws power through the earthed section.

Inline neutral sections have been used on mainlines at up to 200kph; however the geometry can be difficult to maintain, and the glass bead insulators require regular cleaning. Reliability problems in the UK have led to inline types being banned above 160kph for new installations.
The carrier wire type consists of two or more overlaps in quick succession; the first transfers the pantograph from the first live wire run to an electrically floating wire run – the carrier wire; the second overlap transfers the pantograph back onto a second live wire run. Train power is switched off in the normal way. If the route carries trains with more than one pantograph, there are two ways of approaching the problem. If the multi-pantograph trains on the route have electrically common pans via an on-roof 25kV busbar, the CWNS must be made longer than the longest pantograph spacing. If the pans are not electrically common, then either the CWNS is made longer than the longest pantograph spacing, or is shorter than the shortest pantograph spacing.

Alternatively, the arrangement can be extended to three or four overlaps, as used in the UK. Either option must ensure that the incoming and outgoing wire runs are never connected through the carrier wire, pantographs and train busbar.
Figure 133: Series 1 four span carrier wire neutral section for UK; profile and plan views\textsuperscript{74}

Carrier wire types can give better dynamic performance and reliability than the inline type, but require a more complex OLE arrangement and take up much more space. This can make it harder to find a location away from bridges, stations, junctions and signals, but still close to the switching site. Carrier wires were first used on European high speed lines and High Speed One, and are now being deployed in the UK on the GWML.

10.8 Isolators

OLE isolators provide a point of isolation in the traction circuit for the purposes of isolating sections or subsections of OLE (section 9.1.3) for planned or unplanned maintenance. They generally take the form of a horizontal or vertical throw knife switch, which when open provide a visible air gap between the supply and the OLE equivalent to at least Basic Insulation (section 9.8). In their simplest form they are not capable of making or breaking current, and so are only operated once the power supply has been disconnected at the circuit breaker (section 9.2.4). In this configuration the widely used term “switch” is not accurate, and they should correctly be referred to as isolators or disconnectors.

OLE isolators are typically mounted on the lineside, either on OLE masts also carrying support and registration equipment, or on standalone switching structures. Since the live elements are not

\textsuperscript{74} A7100.010.001 “Series 1 Carrier Wire Neutral Section 4 Overlaps Straight Track”, revision C, 2017; Network Rail/Furrer+Frey. Left half only shown for clarity– right half is mirror image on centreline.
insulated or screened, it is essential that the isolator is placed at sufficient height to minimise electric shock hazards.

![Figure 134 (l-r): MLE three position load-break isolator in the open position, and in the closed position. Earth position at rear, vacuum interrupter bottle at front](image)

Isolators can be either **two position** or **three position**. Two position isolators are either open or closed, and provide a simple point of isolation. Three position isolators have a second set of contacts, which can be used to provide an alternate feed path (closed/open/alternate closed) to provide another means to energise a subsection; or to provide an earth connection (closed/open/earthed) to protect staff working on the OLE from inadvertent re-energisation by the ECO making a mistake or by an electric train accidentally entering the isolated section; or (used in the opposite orientation) to earth a feed cable to allow it to be safely worked on. The knife blades and contacts are typically copper or silver-plated copper.
Most switches normally operate in the closed position – they are *normally closed* (N/C) – but some switches, such as those providing alternative feeds or an earthing facility, may be *normally open* (N/O).

OLE isolators can be manually operated or motor actuated. Manual isolators have a simple switch handle at the base of the mast. A padlocking arrangement is provided so that the isolator can be secured in the required position, and each isolator has a unique key which is held inside a locked key box. The key box is then locked with a generic key, and an authorised person can then operate the isolator as follows:

- Unlock key box and remove unique isolator key;
- Operate the isolator to the desired position and lock isolator;
- Remove the unique key and keep it with them, preventing inadvertent re-energisation until all staff are finished work.

Modern installations increasingly use a SCADA (section 9.7.2) operated *motor box* to provide rapid isolation by the electrical control operator.
Regardless of manual or motor actuation, the connection between the actuator and the switch assembly is either a **torsion tube** (for horizontal throw isolators), a **push rod** (for vertical throw isolators) or a **flexible ball drive** (used instead of a push rod). Torsion tubes are the simplest to configure but can be prone to twist failures when actuated after a long unused period, during which the switch blade and jaws can become locked together through oxidisation.

Modern motorised isolators often have a method of remotely detecting that the isolator blade is secured in the correct position, since the security of the isolation depends on it, and the integrity of
the rod mechanism cannot be taken for granted. These isolators have indicator switches fitted to the switch itself, which detect the switch position and report it back via the SCADA system.

Some isolators are required to break load current (section 9.1) so that they can safely be operated without first disconnecting the power supply – these can be properly described as load break switches. In this case there must be a means of extinguishing the electrical arc that will otherwise form as the isolator contacts move apart. This is typically achieved by attaching a vacuum interrupter to the isolator. As the isolator path is broken, the traction current instead follows the path of least resistance through a vacuum bottle, which contains a pair of contacts. After the isolator contacts are safely open, the interrupter contacts are then opened by the actuator, and no arc is able to be struck in the vacuum.

Figure 138: Driescher load-break two position isolator; Swindon, UK
10.8.1 Circuit Main Earths

OLE systems in the UK are now applying the concept taken from the Electricity Supply Industry – that of the Circuit Main Earth (CME). This is an arrangement which will discharge electrical energy to earth in the event of an inadvertent re-energisation of equipment which has been disconnected from its power supply in order to carry out maintenance or repair work.

The CME may be provided either by use of portable earths at a DEP location (section 9.12.1), or increasingly by using a device – typically a motorised two-position (open/earth) isolator with load-break capability. In either case the location must be coincident with a high-integrity cross-bond location (section 9.10.1) to ensure that energy is properly discharged to earth, and within a short distance\(^{75}\) of the location at which the re-energisation could occur.

10.8.2 Feeding Arrangements

The options available for connecting an isolator to the OLE depend on the track configuration. Where the OLE is immediately adjacent to the isolator, a feed wire is run direct to the catenary and

\(^{75}\) In the UK, CMEs must be within 90m of the point of inadvertent re-energisation

Figure 139: Operation of vacuum bottle load-break switch; current flow shown in red
contact wire. However, this is not an option where the feed needs to cross other wire runs to reach its connection point.

In this situation three options are available. The first is to use a candlestick feed arrangement, where a bare feed is run above a suitable portal or TTC boom (section 10.11.4) using a series of insulators on stovepipes. This arrangement has one significant disadvantage: when the wire runs below it are isolated, the live equipment above staff forms a residual hazard. This is often mitigated by lengthening the stovepipes to move the hazard further from the wire runs.

![Figure 140: Candlestick bare feeds along portal boom; Rugby, UK](image)

An alternative is to use a spanwire feed structure. This arrangement uses freely suspended wires slung between lineside masts. Feed wires then run down to the connected wire run. These allow the live parts to be placed higher up, thus reducing the residual hazard. It is also increasingly common to use separate structures rather than the structures used for support and registration, moving the residual hazard away from the location most frequently visited by maintenance staff during an isolation.
The final option (which completely removes the residual hazard) can be applied only if the isolator is switching one track only across a section insulator (section 10.7.1) or insulated overlap (section 10.4). In this case the isolator can be placed directly over the related wire run(s), on a suitable portal or TTC boom (section 10.11.4). Actuation of the isolator is achieved by means of push-rods which run in rollers along the boom from the mast to the isolator, or a flexible ball drive.

A single push-pull rod is now favoured over twin rods in the UK, as this arrangement is easier to set up and does not unevenly load the rods.
10.9 Mechanical Clearances

It is essential to maintain mechanical clearances between static live parts of the system, and those parts which move. Key mechanical clearances are:

- Pantograph (section 10.1) to registration arm (section 10.14.2);
- Pantograph to drop bracket;
- Registration arm to supporting assembly.

Typical mechanical clearances are 15mm for pantograph to registration arm, and 80mm for pantograph to everything else.

10.10 OLE Loadings

All OLE structures must be capable of withstanding a number of loads:

- Permanent Actions (also known as Dead Loads) in the system caused by equipment weight and tension;
- Variable Actions (also known as Live Loads), which may be subdivided into:
  - Environmental loads, created by the action of wind and weight of ice and snow;
  - Accidental loads caused by a dewirement or other temporary situation;
  - Construction loads, caused by the extra weight of staff working on the structure, or unbalanced loads caused by partial installation of equipment.
These load cases must be calculated, Partial Factors (factors of safety) applied to each, and then combined into a set of load case combinations which describe the loads experienced under different conditions. For instance, in the UK maximum wind is unlikely to be experienced at the same time as maximum ice, so the low temperature load case combination applies a reduced wind load. Windspeeds are calculated based on a regional statistically-determined windspeed, modified by the shielding or exposure of the local terrain.

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76 Dead loads are green, live loads in red
77 Dead loads are green, live loads in red, relieving loads in purple
10.10.1 Ultimate Limit State and Serviceability Limit State

The load case combinations are compared with the Ultimate Limit State (ULS) of the structure – that is, the point of mechanical failure. Each load case combination must be less than the ULS – if it is not, then either the design is changed to reduce the loads, or the steelwork size increased.

Structure loads that are checked include normal force (compression/tension), biaxial shear, biaxial moment and torsion. Shear loads and torsion are generally much lower than their ULS capacities, and so structural checks are usually undertaken for the interaction between axial load and biaxial moments for each individual load combination.

ULS checks ensure that the structure will not fail, but more stringent limits are needed to ensure that the OLE performance is not compromised by less onerous environmental conditions. This is done by calculating the Serviceability Limit State (SLS), which is the level of loading needed to deflect the structure to the point that OLE geometry is compromised. Most OLE systems have across-track and vertical deflection limits. SLS tests use lower factors of safety, to reflect the lower risks involved.

The most common form of OLE structural failure is long-term foundation (section 10.12) movement, driven by the overturning moment at the base of the mast; this is easy to detect and can be controlled by height and stagger adjustment and/or structure support measures.

Main steelwork generally only fails due to accidental impact; the failure mode will depend on the steel section used. For instance, the key failure mode for an I-beam structure is known as lateral torsional buckling. This is induced by a moment acting in the direction of the stronger axis, and occurs in structures where the major axis stiffness is far higher than that of the minor axis.

**Figure 145:** Lateral torsional buckling of an I-beam cantilever mast due to additional load of tree falling on OLE in high winds; East Anglia, UK
### 10.10.2 Wind Loadings

ULS wind loads are typically calculated based on a 1 in 50 year return period; that is, the maximum 10 minute mean windspeed which statistics show will not be exceeded over a 50 year period. For SLS checks a 3 year return period is generally used, to reflect the lower risk (and unlikelihood of running trains during a 1-in-50 year storm).

This base windspeed is modified by factors reflecting the local topography, to give the design windspeed or design wind pressure which is used in all wind loading calculations. Wind forces will bear on both the structure itself, and the wires which are attached to it.

**Figure 146: UK isocline map of base windspeeds for wind loading calculations**

### 10.10.3 Ice Loadings

The level of ice loading to be used is determined by the climate in which the system operates; in the UK, radial thicknesses between 3.5mm and 9.5mm are used, depending on location and risk factors.

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78 UK National Annex to BS EN1991-1-4:2005+A1:2010 “UK National Annex to Eurocode 1 - Actions on structures; Part 1-4: General actions - Wind actions”; January 2011; BSI; Figure NA.1
OLE structures play an electrical as well as mechanical role. Mechanically, they must hold the wires at their design positions under a range of environmental conditions, and keep deflections under wind within specified limits. Electrically, they must be capable of withstanding the mechanical stress and thermal stress caused by voltage and current surges under fault conditions.

For AC systems, the structures and their foundations also form a distributed earth system (section 9.10.1), and they must be electrically continuous so that fault currents can pass freely to general mass of earth in the event of an insulator failure. This means that structures are generally formed from galvanised steel (or in some cases, weathering steel), although painted steel structures were widely used historically. Some administrations outside the UK have made extensive use of concrete; although the weight of these can cause constructability issues, and their form of construction is problematic for earthing and bonding when used in AC systems (section 9.10.1).
For steel masts, the form that the mast takes is largely a matter of local preference and the relative cost of hot rolled steel sections, versus welded fabrication of a lattice structure. Using rolled steel gives the advantage of a ready-made section that requires little fabrication other than the welding of a baseplate; whereas a lattice structure reduces the amount of steel used, but requires increased workshop time and the availability of a skilled welding workforce.

Historic and current standards in each administration give rise to a set of standard steel sections. Most systems use standard structure designs which are held in Basic Design Ranges (section 12.1). These designs are pre-approved for use in appropriate locations.

For DC systems, stray currents (section 9.10.2) mean structures must be insulated from earth, and therefore non-conductive materials may be considered.

OLE geometry is controlled at structures in two ways; supporting the OLE means fixing the vertical position. This is usually done at the catenary, by means of a clamp, link or pulley; the contact wire vertical restraint is via the droppers suspended from the catenary. A structure may also be used to register the OLE; that is, to fix the horizontal position. This is done at the catenary, as above; and at the contact wire, by means of a registration arm (section 10.14.2). This is free to move vertically to take account of uplift. Structures for auto tensioned systems also have to allow for along-track movement (section 10.3).

It is sometimes necessary to use a structure for support only (for instance to support the mass of an SI), or to register only (to get a wire run around a heavy curve). These structures are designated as
Not Registered (NR) or Not Supported (NS). Sometimes a wire run may not need any direction connection to a structure and will pass through – for instance a switching structure carrying a feed onto the OLE; these are designated as Not Supported or Registered (NSR).

There are many different types of OLE structure, each appropriate to a particular use.

### 10.11.1 Single Cantilever

The single cantilever is the basic building block of most OLE systems. It is designed to support one wire run over one track.

![Image of single cantilever structure](image)

Figure 149 (l-r): Traditional single cantilever, and Series 1 equivalent with live envelopes shown (insets)

The single cantilever is cheap, easy to construct and adjust, and is the standard structure for use on a two track railway. Efficiently designed railways tend to maximise the use of these structures.

The traditional cantilever shown above left has a large electrically live envelope, and is awkward to construct due to the use of sloping tubes. Recently in the UK cantilevers have been used which have a much smaller electrical envelope (above right) and a rapid adjustment mechanism, so that construction time is minimised and staff safety maximised.

### 10.11.2 Double Cantilever

It is often necessary, particularly at crossovers and overlaps, to support two wire runs over one track. The simplest way to do this is by means of a double cantilever.
The two cantilever arms are separated along track on horizontal spreader channels to allow for along-track movement (section 10.3) without the equipments clashing. Some high speed railways place an overlap on crossovers to avoid using an SI (section 10.7.1), and these systems use a triple cantilever (section 10.5.5) on the same principal as the double cantilever.

The double cantilever illustrates the important principal of *Mechanically Independent Registration* (MIR). This means that each wire run has a support and registration which is independent of any other.

**Figure 150: Typical double cantilever**

In the event of one wire run being damaged, the other should continue to operate within geometrical limits. This has important implications for OLE availability in the event of a dewirement.

### 10.11.3 Back to Back Cantilever

Where there is sufficient clearance, a *back to back cantilever* may be used to support wire runs over two tracks.

This has the advantage of requiring less materials than a pair of single cantilevers.

**Figure 151: Typical back to back cantilever**

However, maintenance access is more difficult if traditional cantilevers are used, since the live equipment on one track must be isolated in order to work on the second track, meaning the railway is closed to electric services. This arrangement can also cause problems with signal sighting (section 14.5) but is often used in tram systems to improve aesthetics and reduce land-take.
10.11.4 Two Track Cantilever

It is often the case that foundation space is only available on one side of a two track railway; either due to a physical obstruction such as signalling equipment, or because signal sighting (section 14.5) requires a clear sight line on the other side. In this case, the Two Track Cantilever (TTC) is used to support several equipments over two tracks.

![Figure 152: Typical two track cantilever](image)

Pairs of TTCs can also be used to aid construction on a four track railway where all-lines closure for portal installation (section 10.11.6) is not practical.

The TTC will experience a higher overturning moment (section 10.10) at the base of the mast, and for this reason the foundation will be larger to resist the moment. TTCs are usually used only where single cantilevers or portals are not suitable.

The TTC above has MIRs, since the wire runs are on separate cantilevers. TTCs are also sometimes configured to use a span wire strung between the TTC mast and a nose assembly at the extremity of the TTC boom; however this arrangement will not be mechanically independent.

10.11.5 Flying Tail Structures

On heavy curves and complex junctions it is sometimes necessary to register the OLE without supporting it, to maintain horizontal geometry. These Not Supported structures are known as flying tail structures.
10.11.6 Portals

For railways with more than two tracks, it is not generally possible to use single cantilevers as there is insufficient space between tracks. For this reason the standard structure for a multi-track railway is the portal.

The structure shown also has MIRs, and it is relatively easy to make adjustments on these structures; however construction or demolition requires a possession (closure) of the railway, and isolation and earthing of all OLE. The use of a crane, along with good access, is also necessary. For this reason, feasibility of construction must be considered when designing with portals.
A portal may be either a fixed or hinged type. The fixed type has rigid bolted moment connections at each foundation and at each corner; this means all structure loads are transferred to the foundation. A hinged or pinned portal will have one or two hinge pin connections, either at the foundations or at the connections between the mast and boom.

Figure 155: Hinge-based portal; Selly Oak, UK

With this arrangement, only the vertical and shear loads are transferred to the foundation – an arrangement which is especially useful on older viaducts, which may not be capable of withstanding overturning moments, or may have limitations on intrusive works due to their heritage status.

Figure 156: Hinge-based portal on viaduct; Glasgow, UK

Figure 157: Portal configurations (clockwise from top left): fully fixed, single pin base, pinned boom, double pin base

79 Note that the pinned boom retains an element of moment transfer into the foundation
It should be noted that, because of the wideway, the configuration in Figure 154 could equally be serviced using a back to back two track cantilever or two single cantilevers and a back to back cantilever. The decision on which to use will be governed by access to the foundation locations, and whether a possession of the track is available.

10.11.7 Headspans

An alternative to the portal in multi-track areas is the headspan structure. This structure comprises two extended masts, with two horizontal tensioned wires (the upper cross span and lower cross span wires) strung between them to locate the OLE. The top wire is a profiled headspan wire, and this provides support to the overall arrangement.

![Figure 158: Typical headspan for four tracks](image)

The headspan has the advantage of being cheaper and easier to install than the equivalent portal. However the headspan is a load-balanced system, where the tensions in the wire runs themselves contribute to the geometric stability. If a wire run breaks, the design geometry will be lost since all other wire runs will be out of balance. This type of structure is therefore not mechanically independent, and a failure means all tracks are out of service. Headspans require regular maintenance to check the span wire tensions, and adjustment of the equipment tends to lead to design and replacement of assemblies. For high speed lines, the mechanical wave created by the passage of a train can also affect adjacent wire runs. Headspans also require larger foundations than portals, to resist the high overturning moments (section 10.10) caused by the headspan tension, and this can cause problems in areas of poor ground. Wire corrosion problems have also been experienced in the UK.

UK-pattern headspans use an inclined tube between the upper and lower span wires – unlike many European patterns. This provides resistance to the twist forces which the radial loads
(section 10.15) would otherwise impart onto the span wires, as well as a connection point for the registration arm (section 10.14.2). UK headspans have no temperature compensation on the span wires, but some overseas systems use a spring tensioner to maintain a quasi-constant tension.

Because of the reliability issues, headspans are best suited to lower speed applications or applications where low capital cost is more important than high availability or performance. In the UK headspans have historically been installed in large numbers; however their poor performance means they are not used for new designs on mainlines.

Headspans are however a good solution to the problem of visual intrusion at sensitive sites such as listed stations; with intelligent design and use of rod insulators, these structures can come close to invisibility.

Figure 159: Electrified platforms using headspans in Span 4, Paddington – a Grade 1 listed station with OLE almost invisible

10.11.8 Spanwire Portals

A compromise can be struck between the performance advantage of a portal and the cost advantage of a headspan, by using a spanwire portal. This uses a portal boom but with a spanwire to fix the registration equipment, thus avoiding expensive stovepipe arrangements. This is not an MIR arrangement, and is generally confined to sidings or complex areas.
10.11.9 Bridge and Tunnel Supports

Wherever possible, OLE passes through bridges without being connected to them. These bridges are free running. Where low headroom or long width makes it impossible to achieve this, it is necessary to attach one or more support and/or registration assemblies to the bridge. This type of OLE arrangement is known as a fitted bridge. Fitting can be done in a number of ways, depending on the type of bridge and the clearance restrictions.

Many existing tunnels are of Victorian build, and pose particular problems for electrical clearances. These can be wired using tunnel cantilevers or tunnel arms. The former is supported from the centre of the arch; the latter from the outside.
Many bridges have flat iron, steel or concrete decks, and pose a problem if the bridge was not designed to take account of OLE clearances. In this case a glass fibre bridge arm can be used. The arm both supports and registers the OLE. The insulator material has some flexibility, and this provides for a reduced amount of uplift to assist with clearances. Thus the OLE is both supported, but also held down, by the arm. Various end fittings are available; a claw-ended arm provides support for a contenary (section 9.8) with a small system height, and a stress-graded arm for twin contact equipment (section 10.14.1) provides a specially shaped fitting which minimises the electrical stress at the live point closest to the bridge, to help prevent flashover.

Figure 162: Tunnel arm arrangement

Figure 163: Glass fibre claw-ended bridge arm (insulators in white); Whitecraigs, UK
Terminating Anchors

Anchors are required wherever a wire run is terminated. They must be capable of withstanding the overturning moment created by the tension in the contact wire and catenary, both under normal operation and in the event of a wire breakage.

Terminating Anchors take a variety of forms. A stand-alone anchor structure may be used, although wherever possible an existing cantilever, TTC, headspan or portal mast is used to keep steelwork costs down.

An anchor structure may be self-supporting; that is, the steel section and the foundation withstand the entire overturning moment; it may use a compression strut on the same side of the anchor as the terminations; or it may be back-tied, where a tensioned tie wire or rod extends from the top of the structure down to a mass foundation at a short distance from the structure.

Figure 165: UK1/Siemens back-tied anti-fall balance weight anchor; Rugby, UK
The back-tied type has the advantage that a significant portion of the tension load is transferred to the mass foundation, and so the steel section and main foundation size may be reduced. The self-supporting type is used where there is no space for a back-tie. Terminating anchors can carry balance weights, spring tensioners (section 10.3) or fixed anchors.

Figure 166: Self-supporting anchor; Glasgow, UK

It is often necessary to terminate a series of wire runs at the end of a set of sidings; in this situation, using individual masts would be inefficient and provide a collision risk for any train which overruns the buffer stop. For this reason a goalpost anchor is generally used.

Figure 167: Tensorex spiral torsion spring tensioners; Lower Basildon, UK
10.11.11 Midpoint Anchors

Full auto tension lengths (section 10.3) require the use of a midpoint anchor to constrain the tension length and prevent along-track migration. The arrangement of a midpoint anchor depends on the type of structures in use. For cantilevers, the MPA is arranged by means of a tie wire which is clamped to the catenary. This wire is terminated at the structure either side to form the restraint.

Figure 169: Tie-wire MPA arrangement for cantilevers

For portals, a direct connection to the portal boom via insulators is generally used. The connection is jumpered to maintain electrical continuity, and a z-dropper may be provided to additionally restrain the contact wire.
For headspans, the MPA cannot be a single point restraint due to the flexible nature of the system. Therefore a distributed MPA is used; the catenary is clamped to the upper span wire over several structures to distribute the load.

10.12 OLE Foundations

OLE foundations play a similar dual electrical-mechanical role to OLE structures; the foundation must withstand the mechanical loads, but also facilitate the flow of fault current to general mass of earth for AC systems (section 9.10.1), or (ideally) assist in preventing it for DC systems (section 9.10.2).

The main component of mechanical load on an OLE foundation is the overturning moment at the base of the mast (section 10.10). This determines the configuration of the foundation, and there are a number of different types, each designed to resist this moment. The type of foundation chosen must be matched to the ground conditions, ground profile and construction methodology.
10.12.1 Planted Mast Foundations

Planted Mast Foundations are formed by setting a polystyrene former into a previously dug hole, pouring concrete around the former, and then inserting reinforcing steel into the wet concrete. The former is then burned away, and an extended mast placed into the foundation and grouted. Although extensively used in early OLE systems, they are no longer favoured, due to the requirement to support the mast while the foundation is curing, the safety risks of excavating deep holes, and the use of chemicals in burning away the former.

Figure 171: Planted mast; Stevenage, UK

10.12.2 Side Bearing Concrete Foundations

A side bearing concrete foundation comprises a cuboid of reinforced concrete, with the long side arranged vertically. The overturning moment is resisted by this long side bearing on the surrounding ground.

A hole is dug, a reinforced steel cage placed in the hole, the foundation poured, and a dressed concrete cap incorporating holding down bolts poured on top of the main foundation.

Figure 172: Bolted side bearing concrete foundation; Stratford, UK

The holding down bolts protrude from the cap, and a bolted base mast is clamped between upper and lower nuts to allow for adjustment of mast verticality.
A variant of this design, uses for more highly loaded masts, is to clamp the mast baseplate directly to the concrete cap. This has the advantage of removing the bending forces on the bolts, but means that no verticality adjustment is available. Accuracy of concrete levelling is essential for this type of foundation.

**Figure 173: Clamped side bearing concrete foundation; Stratford, UK**

Side Bearing foundations are favoured for level ground with a high bearing pressure and good access for appropriate plant.

### 10.12.3 Mass Concrete Foundations

These are used to attach back-ties for anchor structures. They comprise a cuboid of reinforced concrete dug into the ground; an attachment point is provided for terminating the back-tie.

**Figure 174: Mass concrete back-tie foundation; Peterborough, UK**

### 10.12.4 Piled Foundations

Modern piling techniques offer a number of solutions, which are generally used where either ground conditions are poor, or access time is limited.

Like the side bearing concrete foundation, the moment is resisted by the long side of the pile bearing against the surrounding ground. All the types of pile detailed below, with the exception of the driven steel type, have a dressed concrete cap added after piling, to give controlled water runoff and to take the holding down bolts for a bolted base mast.

A bored pile foundation consists of a reinforced concrete cylinder similar to the side bearing type. A boring rig is used to dig the hole in stages, and concrete is poured onto a reinforced steel cage.
placed in the hole. This piling method is only suitable for good ground, since the hole has a tendency to collapse before the concrete can be poured.

An *augered pile* (or to give its full name, *continuous flight augered pile*) is similar to a bored pile, except that the hole is created in one operation; after having placed a short steel sleeve into the ground, a hole is augered down through the sleeve. As the auger is withdrawn, concrete is pumped down the hollow shaft of the auger and into the hole from the bottom upward. A reinforced steel cage is placed into the concrete before it cures. This avoids the problem of hole collapse.

**Figure 175: Augered pile sleeve being driven; Didcot, UK**

A *driven concrete* pile consists of a precast reinforced concrete pile, which is driven into the ground by a series of blows from a piling rig. These are particularly suited to soft ground.

A *driven steel tube pile* uses the same installation technique as the driven concrete type, but the pile is a hollow steel cylinder.

This makes it much easier to drive, and allows driving of long piles in sections, as each can be bolted on as the previous section reaches ground level. The holding down bolts are pre-welded into the top of the pile, making it an attractive proposition for rapid installation. The disadvantage is that the steel can corrode if placed in acidic ground conditions without suitable protection.

**Figure 176: Driven steel tube pile; Iver, UK**

Unlike other foundation types, the steel tube has no bottom to bear on the ground below it, and so relies on *skin friction* to withstand vertical loads. This can make it less effective for heavily loaded anchor portals where the anchor forces bear down on the foundation.
The screw pile comprises a self-driving bore which forms the foundation itself; it is screwed into the ground, and the pile cap or steel grillage added.

10.12.5 Gravity Foundations

A gravity foundation (also known as a gravity pad) takes the form of a shallow cuboid of reinforced concrete, arranged to form a large footprint. The pad is dug a short way into the ground; the moment is resisted by the underside of the pad bearing against the ground below it on the compression side, and the mass of the foundation on the tension side.

Figure 177: Combined gravity foundation for mast and back-tie on viaduct; Fenchurch Street, UK

Gravity foundations are used in locations where depth is not available, such as on viaducts, or where ground conditions below the surface are poor.

10.12.6 Rock Foundations

Rock foundations are used where the railway runs through an area where bedrock is on or near the surface. The rock is usually dressed with a flat concrete bearing face, and holding down bolts are drilled into the rock and bonded with a suitable adhesive. Fractured rock strata can be especially problematic, and grouting or even rock-breaking may be necessary in these cases.

Figure 178: Rock anchor foundation; Sydney, Australia
10.12.7 Attachment to Other Infrastructure

In restricted clearance areas there is often not room for a dedicated OLE structure foundation. Typically, these areas are at:

- Stations;
- Overbridges;
- Underbridges;
- Cuttings with retaining walls.

Figure 179: OLE supported from station roofwork; Manchester, UK

In these areas it is necessary to attach OLE structures or assemblies to the existing infrastructure. For these attachments, the OLE designer must take account of the following:

- Condition of the structure;
- Load capacity of the structure;
- Ownership of the structure (many bridge structures are owned by third parties, who may or may not consent to the fixing);
- Effect of fault current on structure and other systems and utilities attached to it;
- Electrical clearances;
- Fixing arrangements;
- Safety of the public.

Figure 180: Portal mast pedestal on outside of viaduct; Manchester, UK

It is often the case that other assets such as signal heads, CCTV or depot lighting can be attached to OLE structures. In this case it is necessary to consider management of earthing and safe access for maintenance.
10.12.8 Foundation Basic Designs

The basic design range of each OLE system generally contains a number of foundations, which are pre-approved for use at appropriate locations. Foundations are allocated based on the constraints at the location, geotechnical conditions, embankment stability, any environmental constraints, and the construction methodology.

Where standard foundations cannot be allocated, specially designed foundations are used, and these are subject to a civil/structural approval procedure.
10.13 OLE Assemblies

A full description of the often-confusing and contradictory terminology used in OLE design and construction (in common with most engineering sectors) is beyond the scope of this book. The following diagrams give an overview of a few the terms used.

Below is a *pull-off* cantilever; so-called because the assembly staggers the wire toward the mast.

Below is a *push-off* cantilever (sometimes known as a *push-pull* cantilever); so-called because the assembly staggers the wire away from the mast.
10.14 OLE Geometry

The requirement for continuous contact between the OLE and the pantograph means that the geometry of the system must be kept within strict limits. It is important to ensure that the OLE geometry complies with the rules set out below. Failure to do so will compromise the reliability – and potentially safety – of the system.

The contact wire geometry is defined in terms of *height* and *stagger* at each structure. The height is measured parallel to the track centreline; the stagger as the offset perpendicular to it.
10.14.1 Vertical Geometry

The vertical range is limited by the pantograph operating range (section 10.1). Therefore each system has both a minimum and maximum contact wire height. Above the upper limit, the pantograph will auto-drop leading to loss of power; below the minimum height electrical clearances to the train will be compromised. The requirement for height variation arises from the need to achieve minimum safe clearance for road and pedestrian traffic at level crossings (section 14.10), and to operate through low overbridges (section 10.11.9).

Modern high speed lines, however, are usually new construction, with no level crossings (due to the unacceptable safety risks), and overbridges built to give generous clearances. In these circumstances it is possible to maintain a constant contact wire height throughout the route. For instance, in the UK High Speed One has a contact wire height variation of only 0.01m.

For systems where there is a need for height variation, the pantograph has a maximum rate of rise and fall per second, above which it will not be able to follow the wire. Therefore the rate of rise and fall of the wire over the pantograph – the contact wire gradient - must be controlled if good current collection is to be achieved. The maximum gradient is generally proportional to the
maximum linespeed – for instance European Standards\(^{80}\) specify maximum gradients ranging from 1 in 40 at 50kph to 1/1000 at 250kph. A useful rule of thumb for good current collection is:

\[ G_{\text{MAX}} \leq 1 \text{ in (5v)} \]

where \( v \) is measured in mph.

Additionally, areas of gradient change are subject to profile rules as below. Failure to control gradient, and change of gradient, can lead to long term current collection problems and locally increased contact wire wear.

![Figure 184: Typical contact wire profile (y axis exaggerated)](image)

Note that gradients are always measured relative to track gradients rather than a fixed point in space. The maximum gradient generally can only be achieved by means of an intermediate span with a half maximum gradient. Gradient can be quoted either as “x%” (used in Europe) or as “1 in \( y \)” (in the UK).

![Figure 185: Typical twin contact bridge profile](image)

At low overbridge locations, the system height (the distance between the contact wire and catenary) is reduced and catenary (section 9.8) used. For very low bridges the system height is eliminated

\(^{80}\) BS EN 50119:2009+A1:2013 “Railway Applications – Fixed Installations – Electric Traction Overhead Contact Lines”; 31 May 2013; BSI; section 5.10.3
by using a twin contact arrangement, where contenary is spliced into the catenary and then brought down until it is side by side with the contact wire.

The design of OLE through the overbridge itself must be carefully managed. It is essential to maintain sufficient clearance from all live parts – including the pantograph – to both the bridge structure above and to the side, and to the train below. This must include allowances for track maintenance, OLE maintenance, train sway, OLE uplift and the depth of the live equipment itself.

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**Figure 186: Build-up of clearances at an electrified overbridge**

Although the diagram above shows the vertical build-up of clearances under a bridge, this approach is too simplistic to be used on its own. It is essential that lateral clearances are also considered, and as a general rule, the more complex the bridge shape, the more the design has to be considered as a three-dimensional problem. At arched bridges, the pantograph is often the constraining clearance.
If adequate clearances cannot be provided through an existing overbridge, then the air gap must be increased; either by jacking or reconstruction of the bridge, or by lowering the track. Neither of these options is straightforward or cheap.

Figure 187: Mechanical and electrical clearances at a bridge

The design uplift is the uplift the system must be capable of catering for without failure. It is a function of the maximum uplift derived from system modelling, and a factor of safety for the uplift. For European systems\(^{81}\), the safety factor is normally two.

For bridge arrangements where clearances are restricted, support and registration assemblies which restrict the uplift are available (section 10.11.9).

An additional consideration is the span differential for each OLE structure. This is the difference between the span lengths either side of the structure. A large span differential corresponds to a large elasticity differential between the two spans of OLE, and this can affect current collection. Objective evidence of this effect is hard to come by, but nevertheless most UK systems have a maximum permitted span differential.

Conversely, having a large number of equal spans can produce an effect known as galloping where windy conditions can produce a resonant movement of the wire which can lead to dewirement. For this reason many administrations have a limit on the number of equal spans, and require the introduction of a longer or shorter span to break up the resonance.

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\(^{81}\) Ibid.; section 5.10.2
10.14.2 Horizontal Geometry

The pantograph also has a horizontal operating range (section 10.1), and contact wire deviation outside this limit runs the risk of the pantograph coming off the wire. The pantograph will then rise without restraint, and as it interferes with the wire, dewirement is a certainty.

The horizontal displacement of the contact wire from the pantograph centre line at registration points (stagger) is required to ensure even pantograph carbon wear and carry overhead line around a curve.

![Diagram of pantograph and contact wire]

Figure 188: Contact wire (in red) staggered either side of track centreline (chained) on tangent track

This leads to the concept of maximum stagger. The maximum stagger is not usually a constant value; as contact wire height increases, the sway of the pantograph created by train roll increases. This reduces the effective operating range of the pantograph, and so the maximum stagger is linearly reduced to compensate.
The stagger is achieved by restraining the contact wire with a registration arm. This assembly is attached to the structure by means of a drop bracket. The registration arm length is matched to the stagger – a minimum stagger is set – so that the pantograph does not come into contact with the drop bracket when the registration arm is raised to the design uplift. In particular, some arms are designed to reach over the pantograph centre line; others are not.

**Figure 189: Minimum stagger and heel setting**

An associated parameter is that of the heel setting. This is the vertical distance from the contact wire to the attachment of the registration arm to the drop bracket. This, combined with the minimum registration arm stagger, ensures the pantograph does not hit the registration assemblies.

There are a number of different types of registration arm for use in different situations. Most arms on mainline systems are of the curved type to allow for uplift. The amount of curve is a function of the design uplift (section 10.14.1) – higher speed systems require deeper curved arms.

**Figure 190: Mark 1 curved copper registration arm; Bushey, UK**
On slow speed systems where uplifts are smaller, straight arms are often used. These are sometimes also used on mainline systems with a large angle of inclination, to increase electrical clearances or clear a pantograph on an adjacent track.

By contrast, an overreach arm is used to reach over the first contact wire to reach the second at overlaps or turnout control structures.

![Figure 191: HS1 overreach arms; Stratford, UK](image)

A knuckle is a registration assembly designed to provide staggering at a distance from an OLE structure, or where it is not possible to fit a conventional registration arrangement in.

![Figure 192: UK1 knuckle; Rugby, UK](image)

The point where the horizontal operating range is most at risk is at the midspan between the structures. This is because wind forces cause blowoff of the contact wire from its still air condition. This leads to the concept of Maximum Total Offset (MTO). This is the sum of Midspan Offset (MSO), blowoff, and stagger effect. The MTO for each span must be less than the Maximum Permissible Offset (MPO). MPO is derived from the pantograph half width, sway and track tolerances, and includes
a factor of safety to keep the contact wire away from the end of the operational width under all conditions\(^{82}\).

MSO is the distance from the contact wire to the track centre-line under still air conditions midway between registration points. MSO is a function of the stagger at either end of the span, and the track curvature, measured as versine (also known as stringline). It is important to control MSO by varying structure spacing and stagger, since the other factors in the MTO are less easy to control. Smaller structure spacings are needed on small radius curves to keep MSO within limits.

Versine is measured using a straight line drawn from the running rail at one structure to the same rail at the next structure; the distance between this line and the same rail at the midpoint is the

\(^{82}\) “Overhead Line Equipment Design and Pantograph Interface”, K. Warburton; 2015; IET
Versine. Versine is a function of span length and track radius. If versine is too high then MSO will be compromised, and structures spacings must be reduced.

Blowoff is the amount through which the contact wire is moved at the midspan as a result of maximum wind conditions. It is a function of the contact wire tension, the contact wire drag factor (which is a measure of the aerodynamic drag of the wire), the contact wire surface area (diameter \( \times \) length), and the design windspeed.

*Stagger effect* is the difference between the worst deviation in the span under wind, and the deviation at midspan – when the staggers at each end of the span are not the same in magnitude and direction, the MTO may not occur at midspan. The stagger effect figure is added to the midspan offset and blowoff to find the MTO.

Similarly to maximum stagger, MPO is not a constant, due to the increased sway of the pantograph with height. MPO is reduced linearly to compensate for this sway.

*Sweep* is the distance the contact wire moves across the pantograph in the course of travelling between two registration points, be it either from one side to the other, or from one side to the centre line and back again. *Sweep Ratio* is the ratio of this distance to the span length; it is thus a measure of the speed of the contact wire movement over the pantograph.

It is important to keep the sweep ratio between minimum and maximum values across a whole OLE route, since if the contact wire moves too little, the carbons may wear unevenly. This can cause the pantograph to ‘snatch’ as the contact wire passes over the carbon discontinuity. Sweep ratio is less important on individual spans.

## 10.15 Assembly Loadings

The OLE support and registration is subject to a number of mechanical loads. These are;

- *Permanent vertical loads*; the dead loads caused by self-weight of the equipment;
- *Ice vertical loads*; live loads created by the weight of ice on the wire under cold weather conditions;
- *Permanent radial loads*; dead loads caused by a component of the wire tension being transferred to a structure when the wire changes direction due to stagger;
- *Wind radial loads*; live radial loads created by the action of wind on the wire.

The support and registration components must be capable of withstanding all of these loads in combination. In particular, the permanent and wind loads affect the operation of the support and registration assemblies, since registration arms (section 10.14.2) behave poorly if not held in tension. If there is little or no tension, the registration arm will “chatter” at the drop bracket fitting,
and electrical arcing may occur across the fitting, eventually causing failure through erosion. At the other extreme, too much radial load can lead to failure of the registration arm fittings.

If there is a compression load on the registration arm, the combination of self-weight load and radial load results in a downward force, creating a hard spot. In extreme cases the registration arm could flip around, with catastrophic results for the next train. Most systems have special registration arms designed specifically to take a compression load, since there are occasions where there is no other practical option.

![Figure 194: Series 1 compression arm with uplift stop (arrowed); Newbury, UK. Note compressive radial load from wires](image)

For all these reasons it is important to keep the registration arm load within design limits, by adjusting stagger and versine. The effect of versine on radial load is approximately four times that of stagger, so structure spacing on curves is key.

The same limitations apply to a lesser extent on the catenary support; there is a maximum vertical and radial load. Most support arrangements are capable of taking compression loads; however care should be taken with cantilever arrangements which use a top tie wire rather than a top tube, as these can collapse if sufficient compressive radial load is applied.

A Partial Factor (section 10.10) is applied to all maximum loads. This factor of safety is generally lower for registration assemblies than for structures; for instance, UK heavy rail typically uses a factor of safety for assemblies of 1.3 to 1.4.
10.16 OLE Materials

The choice of materials for OLE fittings is critical – the components being subjected to a variety of electrical and mechanical stresses as well as environmental conditions, with very limited inspection and maintenance access.

Figure 195: Modern cantilever showing a mix of galvanised steel, stainless steel, aluminium and cast CUNiSi fittings; Stratford, UK

Most fittings in modern OLE are galvanised malleable cast iron, aluminium or (increasingly) stainless steel and copper alloy. Historically, galvanised mild steel was more common. Moving connections are typically either ball and socket, or hook and eye, to provide the required degree of freedom.

The advantages and disadvantages of various materials are outlined below.

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<thead>
<tr>
<th>Material</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Copper</td>
<td>Excellent electrical conductivity &amp; resilience to fault current</td>
<td>Expensive</td>
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<tr>
<td></td>
<td>Excellent corrosion resistance</td>
<td>Theft risk</td>
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<td>Relatively heavy for a given strength</td>
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<td>Copper Alloys</td>
<td>Stronger than copper, better durability</td>
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<td>(CuNi, CuSn, CuZn)</td>
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<tr>
<td>Galvanised Steel</td>
<td>Low cost</td>
<td>Lower conductivity than copper, copper alloys or aluminium</td>
</tr>
<tr>
<td></td>
<td>Easy to manufacture</td>
<td>Corrosion issues if galvanising is damaged</td>
</tr>
<tr>
<td></td>
<td>Low theft risk</td>
<td>Medium/high weight for given strength</td>
</tr>
<tr>
<td></td>
<td>Commonly available</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Advantages</td>
<td>Disadvantages</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Galvanised Malleable Cast Iron</td>
<td>Easy manufacturing for cast items such as clips and clamps</td>
<td>Not suitable for long items</td>
</tr>
<tr>
<td></td>
<td>Well understood material</td>
<td>Relatively heavy</td>
</tr>
<tr>
<td></td>
<td>Complex shapes can be made</td>
<td>Galvanising prone to damage during short circuits</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>Excellent corrosion resistance</td>
<td>Higher coefficient of thermal expansion than galvanised steel</td>
</tr>
<tr>
<td></td>
<td>Acceptable weight for a given strength</td>
<td>More complex to manufacture</td>
</tr>
<tr>
<td></td>
<td>Good resilience to fault current/temperature</td>
<td>Lower conductivity than copper</td>
</tr>
<tr>
<td></td>
<td>Good atmospheric corrosion resistance in neutral pH atmospheres</td>
<td>Can cause electrolytic corrosion when in contact with less noble metals</td>
</tr>
<tr>
<td>Aluminium</td>
<td>Generally lighter weight for a given strength</td>
<td>More specialist manufacturing, cutting and welding needed</td>
</tr>
<tr>
<td></td>
<td>Low price/weight ratio</td>
<td>Issues around bimetallic corrosion need careful management</td>
</tr>
<tr>
<td></td>
<td>Good conductivity</td>
<td>Prone to damage if handled or stored without care</td>
</tr>
<tr>
<td></td>
<td>Good atmospheric corrosion resistance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>resistance in neutral pH atmospheres</td>
<td></td>
</tr>
<tr>
<td>Aluminium Alloys</td>
<td>Stronger than Aluminium</td>
<td>Lower conductivity than Aluminium</td>
</tr>
<tr>
<td>Tinned Copper</td>
<td>All the benefits of copper, plus: prevents bi-metallic interfaces with aluminium</td>
<td>Expensive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Can corrode if coating is damaged</td>
</tr>
<tr>
<td>Phosphor Bronze</td>
<td>Ideal plain bearing material for used where lubrication is marginal or non-existent</td>
<td>Expensive</td>
</tr>
<tr>
<td></td>
<td>High wear resistance</td>
<td>Hard to form when hot</td>
</tr>
<tr>
<td></td>
<td>Excellent corrosion resistance</td>
<td>Hard to machine</td>
</tr>
<tr>
<td></td>
<td>Low friction</td>
<td>Moderate conductivity</td>
</tr>
<tr>
<td></td>
<td>High fatigue resistance for a non-ferrous metal</td>
<td></td>
</tr>
</tbody>
</table>

Fabricated or forged components are now favoured over castings. Forgings have the following advantages over castings:

- Consistent quality is hard to achieve or detect with casting processes;
- Forged components are generally stronger than equivalent castings due to the smooth metal grain flow and elimination of voids;
• Forgings tend to have better dimensional accuracy than castings and so don’t always require machining.

Forging is however relatively expensive due to the need for machined forging dies, and so is more economical for large quantities. Casting is cheaper than forging, and remains the only choice for complex shapes that are impossible to forge.

The type and quality of welding for OLE components requires careful consideration and quality assurance, since these interfaces are often carrying the heaviest loads.

Catenary wire is usually a copper alloy, but historically cadmium copper and mixed steel/aluminium conductors were used. Other conductors are aluminium, copper alloy, or stainless steel. Non-ferrous materials are used for certain live fittings in contact with copper conductors.

### 10.17 Wire Types

The various wires used in the system are also chosen for their electrical and mechanical characteristics.

#### 10.17.1 Contact Wire

The contact wire has five main requirements:

- To transmit electrical energy along its length;
- To transfer electrical energy to the pantograph (section 10.1);
- To withstand the mechanical stresses placed on it by the tension, environment and passage of trains;
- To withstand wear from the passage of trains;
- To facilitate connection for droppers (section 10.17.4), registration arms (section 10.14.2) and electrical connections.

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83 Cadmium copper is now prohibited in UK installation due to Cadmium’s status as a carcinogen and toxin.
Figure 196 (l-r): 107mm\(^2\) CuSn and 120mm\(^2\) CuAg contact wire. Note single and double identification grooves

Contact wire cross sections conform to a worldwide standard shape, which is a circular section with two notches for connection and support purposes. EU standards are centred on 107, 120 and 150mm\(^2\) sections. Larger sections have a larger wear allowance, but there is a trade-off with the higher weight.

Figure 197: Typical CuNiSi forged contact wire swivel clip; Iver, UK

Contact wire material selection is generally a balancing of the mechanical and electrical requirements. The cross section must be kept as small as possible (to keep weight down) while keeping the conductivity high; however materials with a higher conductivity usually have a lower tensile strength and exhibit long-term stretching under tension, a behaviour known as creep.

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\(^{84}\) BS EN50149:2012 Incorporating corrigenda October 2015 “Railway Applications – Fixed Installations – Electric Traction – Copper and Copper Alloy Grooved Contact Wires”; 31 October 2015; BSI; section 4.5.4
Copper and copper alloy comprise the de-facto standard for contact wires, due to copper’s excellent conductivity, tensile strength and hardness, as well as good performance under temperature change and corrosion resistance. Copper has the advantage of forming a hard but conductive oxidising layer when exposed to air.

**Figure 198: Typical Contact Wire Cross Section**

Alloy additives are added to copper to improve the mechanical performance; however they reduce the conductivity to a greater or lesser extent. Therefore the material is chosen to balance these criteria for the particular system. For instance, hard drawn copper can be used up to a wire temperature of 80°C, beyond which the wire will begin to anneal and lose strength.

**Figure 199: Contact wire strength against conductivity**

If higher operating temperatures are required, silver copper (CuAg) anneals at around 150°C and has otherwise identical electrical and mechanical properties.

One of the key aims of the system design (section 15.1) is to deliver uniform low wear of the contact wire, since the life of a whole tension length (section 10.4) will be reduced should any sections experience excessive wear.

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86 "Overhead Line Equipment Design and Pantograph Interface", K. Warburton; 2015; IET; Section 2
European contact wires use a system of grooves along the top of the wire to identify the material type\textsuperscript{87}.

<table>
<thead>
<tr>
<th>Number of Grooves</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Normal and High Strength Copper</td>
</tr>
<tr>
<td>1 centred</td>
<td>Copper-Cadmium Alloy</td>
</tr>
<tr>
<td>1 offset</td>
<td>Copper-Tin Alloy</td>
</tr>
<tr>
<td>2</td>
<td>Copper-Silver Alloy</td>
</tr>
</tbody>
</table>

### 10.17.2 Conductor Bar

It is sometimes not practical, for a variety of reasons, to provide conventional OLE using flexible wires. In these cases a rigid overhead conductor bar is used. This takes the form of a grooved bar designed to accept a conventional contact wire.

This system is only used in situations where conventional OLE is not feasible, since the bar requires frequent support, and so is more expensive than conventional OLE. However it has a number of advantages, including the lack of tension in the system and the ease of contact wire renewal compared with conventional systems.

\textsuperscript{87} BS EN50149:2012 Incorporating corrigenda October 2015 “Railway Applications – Fixed Installations – Electric Traction – Copper and Copper Alloy Grooved Contact Wires”; 31 October 2015; BSI; section 4.4

![Figure 200: Balfour Beatty overhead conductor bar support; Kings Cross, UK](image)
Typical uses include:

- Tunnels where clearances are too small for conventional OLE supports and conventional levels of uplift;
- Tunnels and stations where fire and public safety requirements are such that a vulnerable tensioned system is not acceptable;
- Locations where OLE design is driven by aesthetic and architectural considerations;
- Locations where retractable or moving OLE (section 13.3) is required.

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![Image 1](image1.png)

**Figure 201 (l-r): Furrer+Frey overhead conductor bar transition, Buschtunnel, Germany; and close-up of bar**

The transition from conventional OLE to conductor bar must be carefully managed since the elasticity of the conductor bar is much lower. This is usually done with a transition bar section which has graduated cut-outs to provide increasing stiffness.
10.17.3 Catenary Wire and Auxiliary Catenary

The *catenary wire*\(^{88}\) – and *auxiliary catenary*, if there is one – has fewer requirements than the contact wire; it is required to transmit electrical energy along its length and to withstand the mechanical stresses placed on it, but not to withstand pantograph wear or transmit energy across a small interface area.

For this reason stranded wires are used for catenary wire. Pre- and post-war systems used hard drawn copper, but in the 1970s aluminium/steel *Alumo-Weld Aluminium Composite* (AWAC) catenary was widely used in the UK for reasons of economy. However this wire has given reliability issues, as the two steel wires – which give the conductor most of its strength – are prone to galvanic corrosion and failure if the aluminium coating is damaged by mishandling or flashover.\(^{89}\)

\(^{88}\) This conductor is known as a *messenger wire* in Europe and the US.

\(^{89}\) NR/L2/ELP/27009/MOD C64 “Overhead Line Campaign Changes – Renew AWAC Catenary prone to failure due to Corrosion of the Stainless Steel Inner Cores”; Issue 1, 2011; Network Rail
Current best practice for catenary is to use copper alloys such as Bz II.

10.17.4 Droppers

All droppers have two main requirements:

- To hold the contact wire at the correct height relative to the catenary;
- To withstand the unloading/loading cycle created by the passage of trains.

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90 OLEMI Drawing 148/075/A3 “Aluminium Covered Steel-Aluminium Conductors”, revision 3; BICC; 1979
Traditionally droppers have not had an electrical function, but modern systems increasingly use *current carrying droppers* with suitable electrical connections to improve resilience to potential differences between catenary and contact wire.

For locations with small system heights, a conventional dropper would be subject to excessive flexing due to pantograph passages, and so an *uplift dropper*, without a fixed catenary connection, is used instead.

![Figure 205: Dropper types (clockwise from left): non-current carrying; chopsticks uplift; current carrying; loop uplift](image)

Droppers (other than uplift types) have historically been made from solid copper wire or galvanised steel wire; however these are prone to long-term failure due to the cyclic loading /
unloading created by the passage of trains. Modern droppers use a stranded copper alloy wire, which is more expensive but gives better load cycle performance.

### 10.17.5 Ancillary Conductors

Conductors which are not contact wire or catenary, but carry traction and/or fault current, are collectively known as ancillary conductors.

Return Conductors (section 9.4.1) have historically used 19/3.25 mild steel or 19/3.25 hard drawn copper, but modern systems in the UK use aluminium as a good balance of conductivity and corrosion resistance versus cost. Current standard wires are 19/3.25 Al (given the codename hornet in British standards\(^9\)) or 19/4.22 Al (cockroach), depending on electrical load. These are used as bare cables in open route, and with a PVC sheath in accessible areas such as stations.

19/3.25 Al is also used for aerial earth wire, although some systems use the All Aluminium Alloy Conductor (AAAC) equivalent 19/3.35 to eliminate creep. 19/3.25 Al (with a PVC sheath) is also used for MSCs and RSCs (section 9.4.5), which being ground-mounted anduntensioned do not suffer from creep.

Figure 207: 19/3.25 PVC sheathed Al cable, used in the UK as bonding cable as well as MSC and RSC. Minus the PVC sheath it is also used as earth wire and return conductor

Cross track feeder wires (section 10.8.2) typically use the same aluminium conductors as return conductors, although more recently 37/2.27 hard drawn copper has been used when connecting to

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copper catenaries, so avoiding the need for bimetallic lugs (section 10.18.2) and associated complex wire connections, which are a known failure mode.

ATF conductors (section 9.4.3) typically use one or two 19/4.22 Al wires (depending on electrical load), but for heavily loaded areas a 37/3.78 Al wire (centipede) is used. Since ATFs are live they need greater sag control than EWs or RCs to prevent them coming too close to the ground. This means higher tension which exacerbates creep, and so recently a 19/4.2 AlMgSi AAAC wire has been used.

Tail wires (section 10.6) must withstand the combined tension of the contact wire and catenary and so are a proportionally larger section. Standard UK practise is to use 37/2.36 hard drawn copper wire.

Jumpers (section 10.4) typically use 40mm² to 70mm² flexible stranded hard drawn copper wire, depending on electrical load.

Bonding cables (section 9.10.1) typically use 19/3.25 or 19/4.22 PVC sheathed Al cable depending on electrical load.

10.17.6 Other Wires

Headspan structures (section 10.11.7) comprise three horizontal wires; from top to bottom, these are the headspan wire, the upper span wire and the lower span wire. These are not current-carrying in normal operation and so are arguably not conductors. The upper and lower span wires are nominally taut and in the UK these use 19/2.1 hard drawn copper, although historically 19/1.85 copper covered steel wire (known as copper ply) was used for reasons of economy. The copper ply is prone to damage if rough handling is experienced during construction.

Figure 208: Headspan span wire clamp and RC support
This led to instances of water ingress and subsequent corrosion, and so as with AWAC (section 10.17.3) a programme is under way to replace them with Bz II.

The headspan wire provides the mechanical support for the whole configuration, and for this function a 19/1.63 stainless steel wire is the norm in the UK. For large headspans these are doubled up to provide sufficient mechanical strength. The vertical headspan droppers which support the OLE registrations typically use solid 8mm galvanised steel wire.

MPA tie wires (section 10.11.11) generally use the same wire as the catenary wire for the system. MPA tie wires are usually tensioned at between 3 and 5kN at the setup temperature for the system.

All of the wires discussed so far are designed to be broadly static, and subject to movement only from wind and passing trains (with the exception of tail wires). Some wires need to withstand frequent and significant flexing without fatigue – for instance the connection between a fixed post insulator and a moving blade insulator (section 10.8) of an isolator. For these connections a flexible braid is used.

Figure 209: Flexible copper braid connection

These comprise a very large number of small diameter strands – usually copper – which are weaved into ropes which are capable of carrying high currents, but remain extremely flexible.

10.18 Wire Connections

A variety of connections are required in and onto OLE conductors, and these can be divided into two groups – tensioned and untensioned. All such connectors are part of the electrical system, and

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NR/L2/ELP/2709/MOD C17 “Overhead Line Campaign Changes – Replace Copper Ply Span and Tail Wire”; Issue 1, 2011; Network Rail
must be able to withstand repeated thermal cycles and fault currents without degradation of the connection.

10.18.1 Tensioned Connectors

These connectors are placed directly into the conductor, either as part of the termination onto a mast or boom, to effect the transition from one wire to another, or to create an electrical break with a cut-in insulator (section 10.19.1). As such they experience the same tension as the wire and are safety-critical, since failure will inevitably result in a dewirement.

For many years the standard means of terminating a stranded wire was a dead end clamp, a cast iron fitting comprising an outer sleeve which carries a clevis, and an inner wedge. For stranded wires, the wire is bent around the wedge, and the tension in the wire pulls the wedge into the dead end sleeve and secures the wire.

For solid conductors such as contact wire, a variation on this design was used with the conductor bent through 90° rather than back on itself.

An alternative for terminating stranded wires was later adopted from the electricity supply industry – the preformed dead-end (also known as a PLP after the manufacturer). This uses a prefabricated set of three copper or aluminium covered steel wire strands (to match the conductor) which are spiral wound, formed into a U-shape and bonded together with a liberal coating of resin and grit. This is then threaded around a terminating casting and the strands spiral wound around the wire in the same direction as the wire layup. The action of the wire tension pulling on the PLP tightens it around the wire, and the friction of the resin coating ensures that the wire does not slip.
Preformed dead ends require a high level of care in installation\(^\text{93}\), and this led to the use of the *cone end fitting*; which uses a conical hollow brass wedge which sits around the central strands of the wire, with the outer strands arranged outside it. The wire tension pulls the conical wedge into a conical gunmetal sleeve which carries the clevis, and the outer strands provide the necessary friction to hold everything in place.

\(^{93}\) An installation video is available online at [www.youtube.com/watch?v=B7zXcSilPc8](http://www.youtube.com/watch?v=B7zXcSilPc8)
Most of these traditional termination devices have now been replaced by the *forked collar socket*. These are a modern form of cone end fitting, but the whole of the wire sits inside a forked collar, which has grooves or *collets* machine into it. These allow the collar’s diameter to reduce as the outer sleeve compresses the collar under tension. The design removes the need for skilled setup and are less prone to failure, but they require a reliable minimum tension to operate correctly, and so low tension wires such as spanwires still use dead end clamps.

It is often necessary to join two tensioned wires together – for instance when joining RCs, EWs or ATFs in long runs, splicing catenary into catenary (section 9.8), or as part of a repair after a dewirement. For many years the standard way to do this was via a *compression splice*. This comprises an double-ended copper or aluminium sleeve (to match the wire) which is internally coated with a conductive grease (to keep out water), into which the wire ends fit. A compression tool is then used to create a series of crimps to hold the wires\(^9^4\).

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\(^9^4\) An installation video is available online at [www.youtube.com/watch?v=K7A_awOllYA](http://www.youtube.com/watch?v=K7A_awOllYA)
This process is time-consuming and easy to get wrong, and so in recent years compression splices have been replaced by double-ended conical couplers. These comprise a CuNiSi barrel and AlBz collet with internal spring-loaded teeth which point away from the direction of tension. The wire simply push-fits into place, and as the wire is tensioned the teeth bite into the wire and secure it. These fittings are much easier and quicker to fit, and are more reliable in use.

None of the above solutions are suitable for joining two lengths of contact wire together – something which is done only as part of a repair, since it introduces a potential failure mode into the most sensitive part of the system; or for terminating an in-running contact wire at a section insulator (section 10.7.1) or in-line neutral section (section 10.7.3). Various designs are available, but all use the contact wire groove (section 10.17.1) to make a connection.

The battleship splice, so-called because of its (alleged) resemblance to a warship, has been used since the 1960s. A set of inclined bolts bear down on the top of the contact wire, cutting into it to transfer the tension to the casting. The bolts are then wired together to prevent loosening.
This was superceded by the *butt splice*, which uses two symmetrical CuNiSi castings clamped via a set of opposing screws. It relies on the friction between the clamp and the contact wire groove.

Special arrangements are required when a wire run is converted to a tail wire arrangement (section 10.6) or tensioned via a single tensioner (section 10.3). The contact wire and catenary are terminated at each end of an *equalising plate* (also known as a *balance plate*) and the tail wire or tensioner connected at the centre.
The ratios of the lengths of the equalising plate arms determines how the tension provided by the tensioner is shared between the contact wire and catenary; equal lengths provide equal tensions, and unequal lengths are used to split the tension unequally between the wires.

**Figure 218: Equalising plate in UK1 wire run; note the unequal lengths used to split the 11.9kN/8.56kN UK1 tensions**

10.18.2 Untensioned Connectors

It is often necessary to connect an untensioned wire to a tensioned one – for instance at jumpers (section 10.4), midpoint connections (section 9.4.2) and switching locations (section 10.8.2). There are a number of ways of achieving this.

*Parallel Groove* (PG) clamps use a similar arrangement to the butt splice above. They come in two variants; one which connects two stranded wires together by clamping around both, and another which clamps a stranded wire to a contact wire (again using the groove).

**Figure 219: PG clamp connection for jumper onto contact wire**

An alternative method which has been used for connecting aluminium wires together is the *Ampact wedge connector*. This uses an aluminium wedge which is driven between the two wires as
they are held in an aluminium C-sleeve. The required amount of compression is achieved by firing a small explosive charge from a specially-designed gun\textsuperscript{95}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure220}
\caption{Ampact wedge clamp connection onto RC}
\end{figure}

In the UK these have been deprecated in favour of a version which uses shear bolts and so does not require specialist explosive charges.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure221}
\caption{Wedge connector – shear bolt type}
\end{figure}

\textsuperscript{95} An installation video is available online at \url{www.youtube.com/watch?v=6TmdxEwLWhI}
Special measures are required when connecting wires of dissimilar metals together, to prevent cathodic corrosion. In this case a bimetallic lug is inserted between the two wires. This is a specially fabricated assembly, which comes in various forms, each including two metals (typically aluminium and copper) friction welded together. These can be used in conjunction with PG clamps or wedge clamps to facilitate joining of copper jumpers to AWAC (section 10.17.3) or aluminium feeder wires to copper RC (section 9.4.1).

When arranging these types of connections, it is important to arrange the aluminium wires and fittings above the copper ones; otherwise any acidic rainfall (a feature of areas with high pollution) will wash copper sulphate (copper wash) onto the aluminium, causing corrosion.

10.19 Insulators

Insulators are required to separate live parts of the system from earthed parts, or to separate electrical sections. The insulators chosen for the system must meet the following requirements:

- Sufficient electrical strength for electrical loads, faults, and lightning strikes, as determined by the insulation coordination process (section 9.8);
- Sufficient mechanical strength for the location and use – including tension, bending or torsional loads;
- Sufficient creepage path for the environmental contamination at the location;
- Sufficient durability to withstand vandalism.
The electrical strength is chosen to match the system voltage. The *creepage path* is the distance measured around the outside of the insulator, and the required distance may be achieved by means of ribbed sections (*sheds* – so called because they are designed to shed water), or they may simply be *long rod insulators*.

### 10.19.1 Materials

The material used for an insulator is dependent on placement, cost and environmental factors. Hard porcelain has historically been favoured in the UK due to its cost-effectiveness and ease of fabrication. However these are prone to vandalism (especially by air rifle) and to explosive failure if moisture ingress occurs. Some porcelain insulators have a hollow gas-filled core, but these are prone to leakage and subsequent failure by the same water ingress mechanism.

In recent years *shed protectors*, comprising a rubber sleeve which fits tightly around the shed, have been added to porcelain insulators. These help the sheds to withstand vandalism, and can hold together a damaged insulator.

Pre-stressed glass is used extensively in Europe, being more robust than porcelain, but also more expensive.

![Lightweight shedded polymeric 25kV insulator; Manchester, UK](image)

Figure 223: Lightweight shedded polymeric 25kV insulator; Manchester, UK

Plastic (or *polymeric*) insulators – comprising a Glass Fibre (GF) and epoxy resin core with silicone sheds - are now standard in the UK, as they are lighter and smaller than their porcelain or glass counterparts, and are naturally *anti-vandal*, since the sheds deform rather than break on impact. However polymers bring new problems – sheds can deform if not stored correctly prior to construction, and Australian administrations have reverted to glass since the local parrots liked to eat the polymers.
Plastic insulating materials may also be formed into rod insulators. These also use silicone over a GF/epoxy core, and are used at locations where clearances to the pantograph are small, and a shedded insulator would be too large. When placing rod insulators into stranded wires, it is important to control the natural torsion which a wound wire applies to the insulator, since rod insulators are very weak in torsion. This is usually managed by means of anti-torsion bars which are clamped to the catenary and contact wire either side of the insulators.

Figure 224: Polymeric 25kV rod tension insulators, with anti-torsion bars; Edgbaston, UK

Glass Fibre insulators can withstand small bending loads, although with a certain amount of flexure. This property is exploited when glass fibre insulators are used as bridge arms (section 10.11.9).

Plastic materials are also used extensively for rope insulators on tram systems.

10.19.2 Mechanical Requirements

The mechanical load requirements of the insulator depend on the use. Tension insulators are designed to take a purely tension load. They are used as cut-in insulation in conductors, and as vertical catenary supports.

Figure 225 (l-r): Insulator types; porcelain cap-and-pin type, and porcelain post type; Euston, UK
They may be formed as individual shed components, joined together by means of a *cap and pin* arrangement to form an insulator of the required electrical strength.

*Post insulators* are designed to take bending and compression loads, and are used to support feeder wires and support catenaries.

Some *switching insulators* are designed to take a torsional moment and are used in torsion-tube operated switches. Others are used in push-rod switches and do not need to withstand torsional moments.

*Glass Bead Insulators* are formed of glass beads threaded onto a rod, and they are used in circumstances where an insulator is required in the in-running contact wire; for instance, at inline neutral sections (section 10.7.3). This type of insulator needs regular cleaning to remove carbon deposited by the pantograph, and their use is therefore minimised.

*Suspension insulators* (colloquially known as *danglers*) are used to support auto-tensioned (section 10.3) wires which only require a small range of movement, typically near the midpoint anchor (section 10.11.11) or fixed anchor (10.11.10) locations. They are also used to support fixed termination ancillary conductors, especially ATFs (section 9.4.3), as they help to equalize the wire tension between spans without imposing high bending moments on individual insulators.

**Figure 226: Suspension insulator for ATF; Cholsey, UK**
11. Signage

OLE is typically provided with a number of signs to:

- Identify the names and locations of equipment;
- Provide a critical means of identifying location during safety-critical communication;
- Ensure that the right piece of equipment is being operated or worked on;
- Give the driver of a train critical information or instruction relating to the traction system;
- Warn of electrical dangers at locations accessible to staff and the public.

The following signage examples are all from the UK; other administration use different depictions and conventions to convey the same information.

11.1 Asset Signage

These signs are provided as a means to identify the names and locations of equipment.

11.1.1 OLE Structure Signage

OLE structures are generally given a unique identification number. In the UK the historical convention has been to use a combination of route code and along-track location. The structure number is in the form [Route code][Unit][Number]. The route code comprises one or more letters.

Figure 227: Structure number plate for the 25th structure in the 29 mile section of the GE mainline; Chelmsford, UK

The unit is either the mile (historically) or kilometre (more recently) within which the structure is located, and the number is a simple increment within the unit. For instance, the first structure at the zero point at London Liverpool Street is B00/01; the route code is B, and the structure is the first

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96 A comprehensive list of UK route codes is available online at Phil Deaves’ railway codes website www.railwaycodes.org.uk/electrification/mast_prefix0.shtm.
in the ‘0’ mile. Subsequent structures are B00/02, B00/03… until the 1 mile mark is reached. The first structure past this mark is B01/01, then B01/02 etc.

Where new structures are introduced on an existing electrified route, a letter suffix is used; so if a new structure is required between B01/04 and B01/05, it would be numbered B01/04A. A second new structure at this location would be numbered B01/04B, and so on.

More recently this system has been replaced by a system which uses the Engineer’s Line Reference – a more widely used route code in the UK – and the along-track kilometrage. For instance, an OLE structure at Didcot on the GWML is numbered MLN85.507 – MLN being the route code and the structure being 85.507km from Paddington.

11.1.2 Wire Run and Section Insulator

UK installations are provided with section numbers at Section Insulators (section 10.7.1), and (more recently) with wire run marker plates at anchor locations (section 10.11.10).

![Figure 228: Section Insulator with number plate; Edinburgh, UK](image)
11.1.3 Switch Signage

All OLE isolators (section 10.8) are provided with a unique number which is marked at the switch location and referenced on the isolation diagrams and instructions (section 15.3.2). Numbering for mid-section switches takes the form [subsection number]/[number of switch in subsection] and switches bridging two sections takes the form [subsection 1]/[subsection 2].

**Figure 229: Switch number plate for switching joining subsection 430D to 431F; Stratford, UK**

11.1.4 Designated Earth Positions

Marker plates are provided at DEP locations (section 9.12.1).

**Figure 230: DEP plate; Darlington, UK**

11.2 Operational Signage

A number of signs are provided to assist train drivers to carry out their duties.\(^97\)

11.2.1 Neutral Section Signage

A *Neutral Section Warning Board* is placed around 1.6km on approach to a neutral section location (section 10.7.3), to give to driver advance notice of the need to shut off power.

\(^97\) G1/GN7634 "Index for Lineside Signs"; Issue 1, September 2015; RSSB; section G2.2.6. Signs themselves are found by searching [Railway Group Standards Online](https://www.railway-group-standards.org/) using appropriate search terms.
A Neutral Section Indication Board is provided immediately on approach to the neutral section to denote the location of the neutral section.

Figure 231: Operational Signage Boards (l-r): Neutral Section Warning, Neutral Section Indication, Lower Pantograph, Warning of Traction System Changeover, Traction Changeover to 25kV AC, Traction Changeover to 750V DC

11.2.2 Power Changeover Signage

These signs are provided wherever trains must change between different electric traction systems, or from electric to diesel traction.

The Lower Pantograph Board is provided at all locations where a bi-mode electro-diesel train is required to switch from electric power to diesel, or a dual-voltage train is required to switch from overhead power to 3rd or 4th rail power.

The Warning of Traction System Changeover Board is placed on approach to an electrical changeover from one system to another. This applies equally to 750V DC third rail to 25kV AC OLE, or vice versa.

The Traction Changeover to 25kV AC Board is placed at an electrical changeover from any other system to 25kV AC OLE.

The Traction Changeover to 750V DC Board is placed at an electrical changeover from any other system (typically 25kV AC in the UK) to 750V DC third rail.
11.2.3 Limit of Electrification Signage

A *No Access to Electric Trains* sign is provided at all locations where an overhead electric train could be mistakenly signalled or shunted onto a line not provided with OLE. Complex locations with a mix of permissible and non-permissible routes for electric trains are provided with additional explanatory text.

![Figure 232: Limit of Electrification Boards; Didcot, UK](image)

11.3 General Safety Signage

A number of different types of warning sign are provided at locations where railway workers or members of the public are in proximity to live parts.

![Figure 233: General Electrical Hazard Sign on station canopy; Didcot, UK](image)
12. Types of UK Equipment

There are approximately 90 different types and subtypes of OLE present in the UK, including tram and light rail systems. The type refers to the generic system, such as Mark 1 or Mark 3b. The subtype refers to the suspension and tensioning system, and the tensions in each wire. A type may have many subtypes; such as Mark 1 has simple and compound, auto-tensioned and fixed termination variants.

The complete list of OLE types in the UK can be found in Appendix D.

Care must be taken when modifying existing equipment, to determine the type in use and ensure that compatible parts are used.

12.1 Basic Design Ranges

A Basic Design Range is a set of drawings which define the components, materials, geometry and parameters of a given OLE system. Each range may contain one or more types of equipment. The allocation designer applies these to a given location in accordance with the requirements of that location.

Figure 234: Typical basic design drawing

The following sections give an overview of the various basic design ranges in use in the UK. Each country will have a set of basic designs in this manner; these are developed appropriate to the technology available at the time, and to the performance requirements of the system.
12.1.1 The MSJ&A Range

The Manchester South Junction and Altrincham (MSJ&A) railway is one of only two routes in the UK to have been energised at three different voltages; it was electrified at 1500V DC in 1931, then converted to 25kV AC in 1971, and then in 1991 to 750V DC to become part of the Manchester Metrolink tram system. Although the original OLE did not survive conversion to 25kV, many original structures remain and are the oldest in the UK. Much of the 750V DC system still uses the previous Mark 3 (section 12.2.1) 25kV support and registration arrangements and insulators.

![Figure 235: 750V DC OLE for trams on original MSJ&A portals with 25kV insulators; Timperley, UK](image)

12.1.2 The GE/MSW Range

The Great Eastern (GE) range was developed by London & North Eastern Railways (LNER) and subsequently BR, and was first installed in 1949 for the electrification of the lines out of Liverpool St at 1500V DC. It was then used on the Manchester to Wath and Sheffield (MSW) route in 1954. The range was updated to reflect the conversion of GE lines to 6.25kV, and the subsequent conversion of both GE and the remaining section of MSW to 25kV AC. GE/MSW equipment, where it remains, is the oldest working type in the UK.

The range is imperial and robustly engineered, using large quantities of copper, which was a cheap material at the time. The range uses painted steel fabricated portals and planted masts, with a large amount of fabrication carried out on site. Most structures are MIR type, with spanwire portals used in complex areas and sidings. The system had a large quantity of fixed termination equipment on running lines – most of which has now been upgraded to the GEFF auto-tensioned
system (section 12.3.2) – as well as auto tensioned equipment for higher speeds. The contact wire, auxiliary and catenary are of a very large cross section, reflecting the original requirement to carry DC currents; this, coupled with the low tension, means system heights are large and supports are substantial. The insulation has been upgraded to 25kV standards, but the configuration of the original DC catenary supports means that electrical clearances are small by modern standards.

![GE compound OLE and anchor portals; Shenfield, UK](image)

**Figure 236: GE compound OLE and anchor portals; Shenfield, UK**

The range is no longer available for design use.

**12.1.3 The SCS Range**

The *Shenfield/Chelmsford/Southend* (SCS) range was first installed in 1956 as an extension to lines electrified using the GE system. The range was also originally 1500V DC, and was updated to reflect the conversion of GE lines to 6.25kV and then 25kV AC.

The range replicated most of the features of GE equipment, including heavy contact wire, fixed termination and compound suspension. As with GE equipment, the insulation has been upgraded to 25kV standards. The range is no longer available for design use.
12.1.4 The Mark 1 Range

The Mark 1 range was developed by BR and Balfour Beatty in the early 1960s for the first phases of WCML electrification. Like the GE range, the assemblies are imperial and use copper. The range also uses painted steel fabricated portals and planted masts. All structures are MIR type, with catenary pulleys. Again, system heights are large (nominal 1980mm). For the first time mainlines were equipped with auto-tensioned equipment, setting the standard for all later equipment types. Mark 1 equipment originally came in simple, compound and stitched variants, but the stitched version was soon abandoned. Simple and compound equipments remain in widespread use today.
The range is no longer available for design use.

### 12.1.5 The Brown Boveri Range

The Brown Boveri range was specified by Pirelli for the second stage of the Glasgow South Suburban electrification scheme, as an alternative to Mark 1 equipment. However this scheme was subsequently taken over by BICC who instead specified Mark 2 equipment (see below). As a result Brown Boveri equipment is confined to the Neilston branch of the Glasgow network. This equipment is unique in the UK in using a simple stitched (section 10.2) configuration.

![Brown Boveri Cantilevers with stitch wire (arrowed); Whitecraigs, UK](image)

**Figure 239: Brown Boveri Cantilevers with stitch wire (arrowed); Whitecraigs, UK**

### 12.1.6 The Mark 2 Range

The Mark 2 range was a short-lived development of the Mark 1 range, and was installed in the Glasgow suburbs in the 1960s. It pioneered the use of galvanised steel support and registration equipment. It remains in use on these lines but is not available for design use.
12.1.7 The Tyne & Wear Metro System

This system was developed in the late 1970s for the electrification of the Tyne and Wear Metro. The system is configured for use as a 1500V DC system, using simple auto-tensioned equipment with a mix of lightweight cantilever and headsapn structures. Some heavily loaded sections use twin contact wire and/or twin catenary to minimise volt-drop.

12.2 The OLEMI System

The OLE Master Index (OLEMI) was initiated in the early 1970s in response to the requirement for cheaper OLE builds, and was still being added to until quite recently. It was developed by BR, is now owned by NR, and consists of approximately 13000 drawings. The OLEMI was developed as a modular system, where a single component can carry out several tasks. It is also a metric system, and was initially developed with mechanically dependent supports in the form of headspans. MIR assemblies have since been added to the range. The range contains the Mark 3, Mark 3a, Mark 3b, Mark 3c, Mark 4, Mark 5 and UK1 ranges, and metric conversion assemblies for Mark 1. OLEMI schemes include the second phase of WCML electrification, the ECML and the southern section of MML. In an effort to reduce structural steelwork costs, the standard system height was reduced (down to 900mm for Mark 3b).

The OLEMI is available for use in modifications and extensions to existing OLEMI routes, but out of favour for new electrification due to its numerous failure modes; it is mature, and no longer subject to update.
### 12.2.1 The Mark 3 Range

The *Mark 3* range was developed in the late 1960s, and introduced headspans in a bid to reduce both capital costs and the ongoing maintenance that painted portals need.

It also pioneered the use of pre-sagged simple equipment (section 10.2) in the UK. The range maximised the use of galvanised steel, in lieu of copper, since prices had risen steeply by this time. Copper clad steel wires were used for headspans, which have since suffered corrosion issues and are now being replaced (section 10.17.6).

![Figure 241: Mark 3 spanwire TTC and single cantilevers; Enfield, UK](image)

### 12.2.2 The Mark 3a Range

The *Mark 3a* range was introduced in the early 1970s as an evolution of Mark 3. It also used headspans, but introduced bridle at the catenary support in order to reduce catenary wear at pulleys. In a further effort to reduce the amount of copper used, AWAC (section 10.17.3) was introduced. Midlife corrosion issues mean that this wire is now being replaced on Mark 3a and Mark 3b installations.
12.2.3 The Mark 3b/3c Range

The Mark 3b range continued the use of headspans and AWAC, but introduced bolted base masts to help speed up construction. Mark 3c was introduced to allow a copper catenary to be used instead of the now-problematic AWAC variant, but is otherwise identical. In the 1990s MIR portal assemblies were also added to the Mark 3b range.
12.2.4 The Mark 3d Range

The *Mark 3d* range was developed in the mid 2000s as an upgrade range for existing OLEMI equipments, particularly for use on the ECML. The range is designed to rectify specific failure modes in Mark 3a and 3b equipment, including problems with AWAC (section 10.17.3) and solid dropper failures.

12.2.5 The Mark 4 Range

The *Mark 4* range was developed in the 1970s as a high speed compound system to support the introduction of the APT (section 7.5) on WCML. It was never implemented.

12.2.6 The Mark 5 Range

The *Mark 5* range is a heavy current version of Mark 3c, using 150mm² copper contact wire. It was used only at Dollands Moor freight yard as part of the Channel Tunnel construction.

12.2.7 The UK1 Range

The *UK1* range was developed in the late 1990s in response to the requirement under *West Coast Route Modernisation* (WCRM) to raise WCML linespeeds. The existing Mark 1 and Mark 3a equipments on the route were not adequate for these speeds, and so an upgrade range was required. The range covers the upgrade of Mark 1 and Mark 3a equipment to either 200 or 225kph, although only the 200kph upgrade was used.
The range was developed by Balfour Beatty and Atkins, is modular and uses aluminium MIR assemblies derived from continental best practise. It is used at existing Mk1/Mk3a locations and for new schemes. The range is now mature, and is not subject to updates.

![Figure 244: UK1 equipment; Ledburn Junction, UK](image)

### 12.2.8 The ATF Range

The ATF range was introduced around 2000 for the upgrade of the WCML to Auto Transformer feeding. It contains a range of AT feeder support assemblies and bridge route solutions. It is mature, and is being used on the Crossrail project and Paddington to Stockley auto transformer upgrade.

![Figure 245: Auto Transformer Feeder support on back of UK1 cantilever mast; Milton Keynes, UK](image)
12.2.9 Other Assemblies

A number of other arrangements exist in the UK, which have not been included in an approved design range, and are therefore not officially available for new use. For instance, under the Euston Remodelling contract on WCRM, new Mk1 FT assemblies were introduced. These are not part of OLEMI or UK1.

12.3 Modern Mainline Systems

12.3.1 The SICAT Range

The SICAT (Siemens Catenary) range was introduced to the UK in 2005 for the Larkhall – Milngavie project, and was subsequently used on the Shields – Gourock project. It uses Siemens SICAT SA medium speed equipment, with aluminium alloy cantilevers and extensive use of side-bolted connections rather than clevises.

Figure 246: SICAT portal cantilevers; Paisley, UK

Unlike other UK systems, heel settings are variable depending on radial load, and so setup requires more care.

12.3.2 The GEFF Range

The GEFF (Great Eastern Furrer+Frey) range was developed by Network Rail and Furrer+Frey for the Great Eastern route upgrade. The range was a response to the poor performance of the ex-1500V DC Fixed Termination equipment on the route from Liverpool St to Shenfield, and provides a lightweight modern sagged simple AT equipment for the existing GE structures. Only the structural elements of the original GE equipment are retained.

The range is based on Swiss practice, and contains a number of first-of-type arrangements for the UK, including double boom anchor portals and Single Insulator Cantilevers (SICs) which give a reduced component count and smaller live envelope, and are easier to install and adjust than conventional cantilevers.
Figure 247: Single insulator MIRs on GEFF equipment; Bethnal Green, UK

Figure 248: Double boom anchor portals for GEFF equipment; Bethnal Green, UK
12.3.3 The Series 2 Range

The Series 2 range was introduced as part of the National Electrification Programme in the late 2000s to provide a reliable medium speed sagged simple OLE system which comprehensively addressed the shortcomings of OLEMI systems.

Figure 249: Series 2 Bonomi cantilever; Glasgow, UK

Initially developed for 160kph, it is a development of Mark 3c, with modern support arrangements including both Bonomi and Furrer+Frey cantilevers.

Series 2 has now been extended to cover speeds up to 200kph and provide TSI-compliance for multiple pantographs, as part of the Master Series catalogue.

12.3.4 The Series 1 Range

The Series 1 range was introduced as part of the National Electrification Programme in the early 2010s as a 2x25kV auto transformer configuration, providing reliable TSI-compliant, multiple pantograph 225kph-rated sagged simple system which comprehensively addressed the shortcomings of OLEMI systems. The system has been installed on the Great Western Mainline and includes a number of innovations designed to improve electrical safety, increase Adjacent Line Open (ALO) working for maintenance staff, and improve installation productivity during short possession windows. The system was developed by Network Rail and Furrer+Frey, and develops some of the arrangements used in the GEFF range (section 12.3.2). The system pioneered the use of single span overlaps without anchor spans (section 10.4.3) and was the first to extensively use land-and-leave structures which have rapid installation connections between masts and booms.
12.4 Other Systems

All of the aforementioned systems operate on UK mainline infrastructure and are owned and administered by Network Rail. The following systems are owned by private operators.

12.4.1 The Alstom Cariboni Range

The *Alstom Cariboni* range was introduced in 2018 for those surface sections of the Crossrail project in London which are not owned by Network Rail. The range adopts typical French componentry with conventional cantilevers and portals, and support and registration arrangements have much in common with the High Speed One range (section 12.4.3); but also adopts elements of UK best practice such as spring tensioners (section 10.3).
12.4.2 The Channel Tunnel Range

The Channel Tunnel range was installed inside the Channel Tunnel between the UK and France in 1994. Although nominally a Balfour Beatty design, it was influenced by French high speed practice, despite the tunnel being limited to 160kph. It uses sagged simple equipment with conventional galvanised steel cantilevers and portals, and glass insulators.
12.4.3 The High Speed One Range

High Speed One uses the only true high speed OLE system in the UK. It was designed by Amec Spie and installed in the early 2000s. It comprises pre-sagged simple equipment (section 10.2) configured for auto transformer feeding (section 9.4.3).

Figure 253: High Speed One cantilever; Stratford, UK

The configuration is typical of French high speed systems, with galvanized steel structures carrying inclined cantilevers, deep curve registration arms (section 10.14.2) and opposing cantilevered ATF hangers. It operates at speeds of up to 300kph.
13. Special Arrangements

The arrangements described so far in this book are for conventional overhead contact systems. However a number of non-standard configurations can be found at locations around the world; these came into being either through historical quirks, technological dead-ends, or as a response to the special conditions within which the system must operate.

13.1 Three Phase OLE

The supply of a single phase OLE system from a three phase grid causes additional complexity (section 9.1.3). A handful of railways have tried to implement three phase AC overhead line – some successfully, others less so. A three phase OLE system allows for easy regeneration of kinetic energy under braking back into the three phase grid, and this made it an attractive option for mountain railways. However any such advantages are more than offset by the complexity of providing two electrically separate contact wires – the traction return rail providing the third phase – and the use of squirrel cage AC motors, which only operate at a single speed. There are now only four such railways operating in the world⁹⁸.

Figure 254: Three phase AC mountain rack railway; Petit train de la Rhune, France. Note the dual contact wires and bow type current collectors

⁹⁸ More information is available online at en.wikipedia.org/wiki/Three-phase_AC_railway_electrification
13.2 Dual Voltage Crossings

There are occasionally locations where two railways of differing voltages cross at grade. The most well-known of these is in Melbourne, Australia\textsuperscript{99}, where the 600V DC tram system crosses the 1500V DC mainline system. At these locations a special OLE subsection is created, which is isolated from high and low voltage sections on either side, but capable of being fed at either voltage. The supply switching is interlocked with the signalling system, meaning the correct voltage is supplied for the tram or train due to cross.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{crossing_melbourne.jpg}
\caption{1500V DC train meets 600V DC tram; Kooyong, Melbourne}
\end{figure}

\textsuperscript{99} More information is available online at en.wikipedia.org/wiki/Trams_in_Melbourne#Tram-train_level_crossings
13.3 Moveable OLE

There are a number of scenarios where it is necessary to provide OLE that is capable of being moved. This requires special arrangements, both mechanically and electrically.

A common scenario is in maintenance depots, where for shunting convenience OLE is generally provided into the inspection and maintenance sheds, but where this OLE then poses a safety hazard and prevents access to the roof on the train. Modern rolling stock often maximises passenger capacity by moving air conditioning and other equipment into the roof space, meaning maintenance access is necessary.

Figure 256: Retractable conductor bar; Temple Mills, UK

The standard solution is therefore to provide a rigid conductor OLE system (section 10.17.2) on supports which can swing horizontally through 90°, or lift vertically, retracting the OLE away from the train and allowing access. This system is electrically interlocked with the depot power supply and staff warning systems, so that the OLE cannot be retracted until it is isolated and earthed, and staff will not receive permission to access the roof until that process is complete.

A more technically demanding problem exists where a railway crosses a navigation channel by means of a lifting or swinging bridge. It is usually not practical to raise the level of the bridge or make it fixed, since shipping has guaranteed access upriver. In this case it is necessary to build an OLE arrangement which can swing or raise/lower with the bridge. As with depot systems, rigid overhead bar is an ideal solution. Unlike depot OLE, these systems often need to operate at significant speed, and the transfer mechanism from fixed OLE to moving must be carefully designed to ensure that alignment and elasticity change is carefully managed. Electrical and mechanical interlocking is provided, so that the bridge cannot move until the supply is isolated and any transfer mechanism is retracted.
Some electric freight railways have a requirement to load hopper wagons from above, and so it is necessary to have a break in the OLE. This can be achieved by having anchor portals either side of the hopper feed, with skid arrangements in the contact wire to manage the pantograph as it leaves and re-joins the OLE at slow speed.

Figure 257: Bascule bridge with overhead conductor bar; Peenebrücke, Germany
14. Interfaces with Other Systems

OLE interfaces with almost every other railway system. It is often at the interfaces that unexpected failures can occur; for this reason it is vital these are fully considered in the design process. The key interface issues to be considered during OLE design are discussed below.

14.1 Permanent Way

This is one of the most important interfaces, since the OLE must follow the track geometry. Particular items to understand are:

- Track position;
- Track lift, slew and change of cant (for projects with an element of track modification);
- Position of toes of points;
- Areas of reduced track stability (when constructing adjacent foundations, particularly in hot weather when rails may be beyond their stressing temperature and prone to buckling).

14.2 Geotechnical

This is also a key interface, since it determines the long-term stability of the OLE. Particular items to understand are:

- Natural ground types (in cuttings and flat ground);
- Made ground types (on embankments);
- Slope stability;
- Grouting, toe loading and other slope remediations.

14.3 Civil & Structural

Key civil and structural issues to be considered are:

- Electrical clearances to overline structures;
- Attachment to structures.

14.4 Signalling

Key signalling interfaces are:

- Electrical clearances to signalling structures (from RCs, ATFs, OLE, and pantograph);
- Signal positions with respect to overlaps and neutral sections;
- Conflicts with signal sighting requirements due to OLE ‘clutter’;
- Earthing & bonding.
14.5 Signal Sighting

Most railways worldwide still keep trains apart by means of line of sight signalling, meaning that the driver must be able to clearly see signal indications in good time to act on their instructions. OLE equipment can interfere with the sight lines, meaning that the driver has less time to read and understand the signal. In the past poor signal sighting has caused accidents, and in the case of Ladbroke Grove (1999) 100 30 people died in a head-on collision after a new OLE installation obscured a critical signal aspect.

![Figure 258 (l-r): Traditional and virtual signal sighting methods](image)

For that reason, electrification design for line of sight signalling systems must include a robust signal sighting process. This process uses on-site target boards, 3D modelling techniques, or a combination of the two, to determine the impact of new OLE on the driver’s view of the signal aspects. Any OLE design modifications will then be made as necessary to provide minimum reading times for the driver. Masts on the inside of curves typically form the bulk of the obscurations, but for gantry signals, support and registration equipment can also interfere.

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100 Accident report is available online at [www.railwaysarchive.co.uk/eventsummary.php?eventID=142](http://www.railwaysarchive.co.uk/eventsummary.php?eventID=142)
14.6 Telecoms

The key telecommunications interfaces are:

- Electromagnetic Interference (EMI);
- SCADA.

14.7 Electrical & Mechanical Services

*Electrical & Mechanical (E&M) Services* include all non-electrification power supplies, as well as water courses, drainage, water and gas services. The key interfaces are:

- **Signalling Supply Points** (SSPs – a backup feed from OLE for signalling systems);
- Earthing & bonding of LV systems and exposed metalwork;
- Overhead power wires;
- Gas & water pipes;
- Buried power cables;
- Telecommunication cables.

14.8 Stations

Special arrangements are needed at stations, due to the interface with a diverse – and sometimes unpredictable – general public. Typical restrictions at stations include:

- No live equipment over platforms – although some administrations permit up to 50% of an insulator to cross the platform edge;
- All live parts including the pantograph to be at least 3.5m stringline from platform surface\(^{101}\);
- ATF routing away from platforms or in protected ducting;
- Earth wire protection from vandalism;
- Anti-climbing measures;
- Integration of traction bonding with station LV bonding.

\(^{101}\) GL/RT1210 “AC Energy Subsystem and Interfaces to Rolling Stock”; Issue 1, December 2014; RSSB; section 2.2.2.1
It may be necessary to apply special arrangements in order to meet standing surface requirements (see section 9.8) – this can include special earthed cantilevers or opposing staggers to keep live equipment sufficiently far away from the public.

14.9 Operations

Operations requirements are determined in terms of:

- Lines to be electrified;
- Types of electric train required to run, number and spacing of pans;
- Sectioning requirements;
- Pantograph interface;
• Reliability;
• Availability;
• Maintainability;
• Safety.

As well as defining the core lines to be electrified, consideration must be given to non-electrified lines which diverge from, and converge with, the electrified lines. Depending on the signalling and traffic management system to be used, there may be a small but significant risk that an electric train is accidentally misrouted onto a non-electrified line. In this case overrun protection will be provided in the form of a short section of live operational OLE on the non-electrified line to provide protection against dewirement as the pantograph leaves the electrified line. This protects both OLE and pantograph from damage, and facilitates recovery of the electric train. This provision is generally only provided for tracks with a permissible signalled move from the electrified to non-electrified line.

![Diagram of Overrun protection and passive provision for future electrification]

Figure 261 (l-r): Overrun protection and passive provision for future electrification

At key junctions it may be necessary to go further and provide full passive provision for future electrification of the diverging route. In this case the provision is expanded to cover both diverging and converging tracks, and the extent can be increased to provide a complete half tension length (section 10.4) on all lines, which can later be temporarily converted to a permanently earthed section (section 9.12.2) during construction of the new electrified line. This allows construction to be undertaken without isolation of the existing route. The additional OLE will be terminated at an overlap to facilitate future extension.

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102 In the UK the standard provision is 7.5m of OLE per kph of diverging linespeed. NR/L2/ELP/27715/02 “Overhead Contact System Design Specification: Allocation Design Principles”; Issue 1, March 2018; Network Rail; section 13
14.10 Highways

The key interface with highways for mainline railways is at level crossings. Special safety arrangements are needed wherever OLE crosses a public right of way. National standards will typically specify minimum wire heights to be observed under all environmental conditions, based on national road vehicle height standards and typical crossing usage. For instance, UK standards\textsuperscript{103} specify 5.8m as the minimum wire height for all road crossings, and 5.2m wire height for foot and bridle crossings.

Figure 262: Typical hazards at an electrified level crossing; Enfield, UK

It should be noted that many vehicle crossings in the UK are for private access to farmland, and as such the user may be regularly crossing with over-height vehicles. It is therefore important to risk-assess each crossing prior to undertaking the OLE design, to ascertain what control measures are needed to protect crossing users and the railway. Additional mitigations may be imposed, such as height barriers on the road approach to the crossing.

A further consideration for the many user-worked crossings in the UK is that they rely on the pedestrian crossing user to visually check for trains before crossing. OLE masts can reduce the user’s sighting distance, and so a sighting assessment must be undertaken similar to that for signal sighting (section 14.5). This may recommend the relocation of OLE masts to improve sight lines,

\textsuperscript{103} GL/RT1210 “AC Energy Subsystem and Interfaces to Rolling Stock”; Issue 1, December 2014; RSSB; table 3
but ultimately the best mitigation is crossing closure in conjunction with an alternate means of safely crossing the railway.

For tram and trolley systems, highways interfaces are multiple and complex.

14.11 Environment

Environmental interfaces include:

- Visual impact;
- Ecology and flora impacts;
- Vibration and noise impacts on local people.
15. OLE Design Process

The design of OLE is subject to a strict process designed to ensure that designs are safe, robust and meet the performance criteria. These procedures are country-specific; however the principles are the same for all systems.

This section focuses on the general principals, with examples of UK practise used to demonstrate the process.

15.1 Design Categories

There are five stages of OLE design which must be undertaken before construction can be completed:

- **Mechanical system design** is the matching of mechanical and electrical parameters to a railway performance specification, to produce basic wire run parameters (wire sizes and tensions) – typical output being a system description manual;
- **Electrical system design** is the determination of how and where the railway will be fed and sectioned – typical outputs being the major feeding diagram (section 15.3.1) and preliminary section diagram (15.3.2);
- **Basic design** is the creation of components and assemblies for a system, together with detailed geometry and load rules – typical outputs being basic design drawings (section 12.1);
- **Allocation design** is the application of basic design assemblies to a location to meet system design requirements – typical outputs being layout plans (section 15.3.4) and cross sections (section 15.3.5);
- **Construction design** is the controlled change to an allocation design during construction.

15.2 Form A and Form B Processes

The Form A and Form B processes are used in the UK to control OLE designs. The Form A process controls the production of an Approval In Principle (AIP) design. It defines the design outputs, the standards to be met, and the client approval process. The Form B process works in the same way for a detailed design.

15.3 Allocation Design Documentation

OLE designs for specific locations are presented in a standardised manner by a series of drawings and documents. This is to ensure that the details are easily understood by any competent person, and that no ambiguity can be present in the design.
It should be noted that any proposed alteration to OLE will affect some or all of these drawings. Additionally, many changes to other railway systems will have an impact on the OLE drawings.

In the UK no written standard for drawing formats exists; however there are several examples of industry best practice in circulation. Detail of drawing formats tend to be agreed on a project by project basis, with specific preferences depending on the region or person involved.

These drawings form a hierarchy; each drawing overlaps with the one above and below in terms of information. In the following sections this hierarchy is followed in descending order.

### 15.3.1 Major Feeding Diagram

The *Major Feeding Diagram* (MFD) shows the interface between the electricity supply authority and the railway; feeder stations, TSCs, AT sites and neutral sections are included.

![Figure 263: Typical MFD detail](image)

### 15.3.2 Section Diagram, Isolation Diagram and Switching Instructions

The *section diagram* sits below the MFD and show the detailed electrical feeding & sectioning. It details switch numbers and locations, booster transformers, section numbers, and protecting signals. The drawing will be in a preliminary state at the start of the project, and structure numbers and other details will be added as the detailed design progresses.

At the completion of a project and prior to energisation, the section diagram is converted to one or more *isolation diagrams*. These documents are used for taking isolations and are therefore safety critical. These drawings are strictly controlled by the infrastructure owner.
Alongside the isolation diagrams sit the switching instructions. These are a set of procedures detailing the steps to be taken to isolate and earth a particular section. These are also strictly controlled.

### 15.3.3 Wire Run Diagram

The Wire Run Diagram is a schematic showing the wire run numbers, and their anchor locations for a given route. It is typically produced for large electrification schemes, and is a useful tool for planning wire run design and construction.

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104 Health warning added by author
15.3.4 **OLE Layout Plan**

The **OLE layout plan** is the first drawing to show any geometric detail of the OLE. It is typically drawn at 1:500, and shows OLE structures, wire runs, RCs, ATFs, earth wires, overlaps, SIs, track curvature, span lengths, height & stagger and other plan information.
15.3.5 OLE Cross Section

The OLE cross section drawing shows detail of a specific cross section across the railway, including one or more OLE structures.

Figure 267: Typical cross section detail – sheet 1

These drawings are typically 1:100 scale and include all the arrangements, dimensions, and assembly part numbers required to build the structure(s). The assembly part numbers are drawn...
from the basic design range for the system. The drawing may have more than one sheet – for instance it may be split into support and switching sheets for complex arrangements.

15.3.6 OLE Bridge Drawing

The OLE bridge drawing is a set of drawing sheets showing the detail of an overbridge with OLE attachments. These are typically comprised of a layout plan extract, at a larger scale, and a set of cross sections showing the bridge attachments, and a bonding plan extract.
15.3.7 Conductor Schedule

The **conductor schedule** lists all of the contact wire, catenary, earth wire and ATF wire types and lengths to be used on a particular section of electrified railway.

15.3.8 Bonding Plan

The **bonding plan** shows the detailed arrangements for the traction earthing and bonding. For the reasons given in section 9.10 they often show signalling bonding as well. These **composite bonding plans** are generally owned by the signalling discipline, with joint input by signalling and OLE Engineers.

Composite bonding plans are safety critical and are strictly controlled by the infrastructure owner.
15.3.9 Dropper Tables

The *dropper tables* detail the lengths and positions of droppers in each span, to give the correct profile for the particular equipment type.

15.3.10 Bill of Quantities

The *Bill of Quantities* (BoQ) is a breakdown of the assemblies shown on the cross sections into components, for use in the procurement of materials.

15.3.11 Supporting Documents

An OLE design typically includes a number of other supporting documents. These include *hazard logs*, *design decision logs*, *foundation schedules* and supporting narratives explaining the basis and rationale for the design.

15.3.12 Testing & Commissioning Plan

Where changes are proposed to the feeding, switching and sectioning of OLE, a *Testing & Commissioning* (T&C) plan is required for the work. This details the steps to be taken to ensure that the system has been installed as per the design; particularly in terms of feeding, switching, sectioning and insulation strength.
The T&C plan will detail the tests to be carried out prior to re-energisation, as detailed in section 17. The plan should be created in conjunction with the OLE installer so that the logistical requirements are taken into consideration.

### 15.3.13 Operation & Maintenance Manuals

Where new equipment is introduced to the system as part of a construction activity, a set of *Operation and Maintenance* (O&M) manuals are required. These give details of the O&M requirements of the new equipment, so that operations and maintenance staff can conduct familiarisation training.

In the UK, the O&M requirements for standard types of OLE are detailed in a set of standards documents. Therefore O&M manuals are only required if novel items are introduced in the design.
16. OLE Construction

It is essential to consider the construction of OLE at the planning and design stages, since construction is by far the most costly part of the process. Efficient working is only possible if the design is matched to the site and access constraints, and the labour, materials and plant to be used.

Figure 271 (l-r): OLE steelwork and SPS installation; Didcot, UK

The sequence for installation of OLE is generally as follows;

- Foundation installation;
- Mast erection;
- Boom erection;
- *Dressing* of steelwork (adding support fittings);
- Installation of support and registration (also known as Small Part Steelwork or SPS) assemblies;
- Wiring installation;
- *Cutting in* of section insulators and other inline assemblies;
- Registration of wiring (which may be combined with wiring installation in a *high output* system);
- Switching and feeding connections;
- Final wiring adjustment;
- Pantograph running check (*panning*)

Feeder station works may be carried out in parallel with the OLE works, with connections made near the end of the process.
Particular construction factors that should be considered during design are:

- Foundation methodology;
- Site stores for materials;
- Materials lead times;
- Concrete availability and curing time;
- Site access for labour, plant and materials;
- Crane access and ground stability;
- Possession requirements;
- OLE isolation & earthing requirements;
- Impact on adjacent residents and wildlife;
- Integration with other works, such as permanent way, civil, and signalling.

Construction often takes place on an operational railway; in this case, closure and isolation opportunities may be infrequent and short in duration. The design must be staged to take advantage of these opportunities, with as much preparation work as possible carried out with trains running.

It is important that the designer is involved with the construction phase of the work. It is rare that an OLE design is installed without any changes being required; for instance as a result of unrecorded buried services, entailing the moving of a structure from its design position. It is essential that this design change is done by a controlled process known as Construction Design (section 15.1).
17. Testing and Commissioning

New OLE installations must undergo a number of electrical and mechanical tests prior to entry into service. Depending on the extent of the changes and the level of novel design, any or all of the following tests may be needed.

17.1 Type Testing

*Type Tests* are carried out on components and assemblies of a new type, prior to their first use in a system, or use in a different system which will subject the item to new electrical or mechanical loads.

The nature of the type test will depend on the component, but will typically comprise one or more electrical and/or mechanical tests using loads significantly above the expected maximum loads in service. These tests may be to destruction, and are designed to establish the operational envelope of the component so that the maximum *working load* can be established and factors of safety confirmed.

The component may also be subjected to accelerated operating cycle tests, designed to simulate a working life in a much shorter space of time.

17.2 Snagging Walkout, Acceptance Tests and Completion Documents

It is an essential precursor for all of the subsequent tests that the construction is completed in accordance with the system and allocation designs (section 15). This is usually confirmed by means of a *walkout* on site by senior representatives from design, construction, asset owner and maintainer. The walkout will identify any *snags* or corrections that need to be made prior to testing and entry into service. The walkout should be supported by completion documentation from the installer, recording the installed geometry, concrete *cube tests* and other important compliance evidence. These records will be checked against the *acceptance criteria* for the system, such as maximum stagger, gradient and other system parameters.

17.3 Pressure Testing

Insulated cable elements of the OLE system, such as feeder cables at switching sites and ground level ATF routes, require electrical *pressure testing* to ensure that the insulation has not been compromised during installation. This test involves a voltage significantly above the operational
level to be applied to the cores; for instance, UK standards\textsuperscript{105} specify a test at either 75kV DC for 15 minutes, or 44kV AC for 5 minutes.

### 17.4 Section Proving

This is a series of tests to confirm that the electrical sectioning (section 9.1.3) is as designed. Each electrical subsection is switched in turn – starting from the feeder station and working outwards – and each OLE subsection is then proved dead and live. This is done using a live line tester which is an insulated pole connected between the OLE and the traction return rail. The pole allows a small leakage current to flow, which shows live via an indicator LED. These tests also act to test the electrical integrity of the isolators (section 10.8) when open and closed. These tests take place during a complete railway shutdown with all non-essential staff removed from site; and due to the safety critical nature of the test it is essential that both the ECO (section 9.7.2) and the site testers follow a strict test plan, and that the live line tester is always connected to traction earth before any test – live or dead – takes place.

**Figure 273: Section proving with a live line tester; Stockley, UK**

### 17.5 Short Circuit Testing

This test is designed to prove that the electrical protection (section 9.7.1) works as designed, and that all lineside equipment is fully immunised (section 9.4) under the most onerous conditions. One or more electrical faults are deliberately introduced to live OLE – usually using a portable isolator test rig to connect the OLE to traction earth – and the performance of the electrical protection and the circuit breaker monitored during the subsequent electrical trip. Short circuit tests are carried out under the strictest of test conditions.

\textsuperscript{105} NR-PS-ELP-00008 “Product Specification for High Voltage Cables and Accessories for Traction Supplies”; Issue 3; December 2005; Network Rail; Appendix B
Measurements taken during these tests include rise in earth potential, feeder current, fault clearance times and return current paths during the fault and data packet monitoring for the signalling system.

17.6 Unpowered Pantograph Testing

This test is designed to validate the dynamic performance of the mechanical system, without introducing the additional risk of powering an electric train from the new OLE. The test uses a special test coach which carries an instrumented pantograph, and is pulled by a diesel locomotive. The test coach will generally run at increasing speeds as the test proceeds, and records contact force and height and stagger data, as well as video of the pantograph. Any such train is treated as though it was electric for operational purposes, since it is in contact with the OLE.

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106 In the EU these tests are carried out against BS EN50317:2012 “Railway Applications – Current collection systems - Requirements for and validation of measurements of the dynamic interaction between pantograph and overhead contact line”; 29 February 2012; BSI
17.7 Full Dynamic Testing

This test may also cover the areas described in the previous section, but will also confirm the expected electrical behaviour by using an electric train of the type planned for use on the electrified route. This is often combined with contemporaneous testing of lineside equipment to confirm immunisation levels (section 9.4) are as planned.

Figure 275: Typical output from instrumented pantograph on test train\(^{107}\)

\(^{107}\)Trace lines are stagger (red), height (green) and contact force (dark blue)
18. OLE Maintenance & Renewals

It is important to consider the maintainability of OLE at the planning and design stages, and OLE is relatively maintenance-free compared with other railway systems if designed correctly. It is usually inspected periodically, and any maintenance is carried out by small teams working from rail-mounted scissor lift or cherry picker platforms.

Depending on the age and type of the equipment, regular maintenance items can include:

- Checking component condition, corrosion and position;
- Checking and cleaning insulators;
- Checking and adjusting height and stagger;
- Adjusting and cleaning neutral sections and section insulators;
- Checking mechanical and electrical clearances;
- Checking continuity of electrical connections;
- Checking wire tensions;
- Mechanical wear (for instance on hinge pins – typically checking a percentage of fittings);
- Greasing connections;
- Structure painting (for older non-galvanised structures);
- Checking contact wire wear;
- Campaign change replacements of known problem components.

Maintenance periodicity depends on age of equipment, traffic levels, criticality of the route, the matching (or otherwise) of pantographs and OLE, and the availability of access.

Contact wire will need replacing as part of a midlife renewal at typically 25% to 33% wear, which is generally 20 to 30 years after installation. Leaving contact wire in situ significantly beyond this wear level creates a risk that dropper clips and other contact wire connections are impacted by the pantograph, and erodes the ability of the wire to withstand tension, leading to parting and dewirement. Midlife renewal may also address other issues which have come to light since installation.

More onerous rectification work is required after a dewirement. The team will be required to bring the OLE back into service as quickly as possible, and new wiring and support assemblies may be required. Each area has a store of materials for use in such incidents.

\[\text{108} \] Modern systems are usually grease-free.
19. Remote Condition Monitoring

The lack of redundancy in the OLE system makes it very important to understand and control the condition of both the infrastructure and the train-mounted equipment. In recent years an increased emphasis has been placed on the use of automated monitoring systems to augment the normal visual inspection processes.

19.1 Lineside Pantograph Monitoring

Monitoring of pantograph condition may be undertaken from a fixed lineside location using various techniques. *Panchex* is a system which has been used at critical locations on the UK electrified network since the 1980s, and is designed to detect faulty pantographs. The system comprises a linear sensor attached to the contact wire, which measures uplift (section 10.1.2) as each train passes. The system is synchronised with the *train describer* system which the signaller uses to identify each train. In this way a train with a faulty pantograph can be quickly taken out of service before the fault causes a dewirement.

*Figure 276: Panchex uplift monitoring; West Coast Mainline, UK*

This system has the disadvantage of requiring equipment to be placed in the OLE system itself, and requires ongoing maintenance. It is now being replaced with the *PanMon* and *Pantobot* systems, which use 3D photogrammetry techniques to detect faults in passing pantographs, and thus do not need any connection to the OLE.

19.2 Train-Mounted OLE Monitoring

Many administrations now use a dedicated OLE monitoring train, which passes over the electrified network at standard intervals and provides dynamic monitoring (section 17.6) through an instrumented pantograph. This is often tied into a Global Positioning System and allows faults to be accurately located for rectification. Some train operators are now applying these systems to a small number of service trains, which travel key routes at much higher frequencies and so can spot trends earlier than a dedicated train.
Figure 277: High speed Shinkansen class 923 OLE monitoring train, a.k.a. “Dr Yellow”
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**UK Electrification Build History 15/12/2018**

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**Table Notes:**

- **Voltage** indicates the voltage used in the electrification process.
- **Contact** denotes the contact type used in the electrification process.
- **To** specifies the destination of the electrification route.
- **Expenses** list any associated expenses or costs.

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**UK Electrification Build History:**

- **1992 - 2018**
- **Conversion: 1992**
- **Conversion: 2006**
- **Conversion: 2008**
- **New Build: 2000**
- **New Build: 2013**
- **New Build: 2016**
- **New Build: 2018**

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**Projects Covered:**

- Conversion: 1992
- Conversion: 2006
- Conversion: 2008
- New Build: 2000
- New Build: 2008
- New Build: 2016
- New Build: 2018

---

**UK Electrification Projects:**

- **25kV 50Hz AC**: Manchester - Sheffield, Manchester - Leeds, Manchester - Crewe
- **±25kV 50Hz AC**: Edinburgh - Glasgow, Manchester - Crewe, Liverpool - Manchester
- **750V DC**: London - Brighton, Manchester - Liverpool, London - Edinburgh

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**Key Details:**

- **Voltage Contact Position Date Type**
- **Page 2 of 2**

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**Project Details:**

- **25kV 50Hz AC**: London - Brighton, Manchester - York, Liverpool - Manchester
- **±25kV 50Hz AC**: Edinburgh - Glasgow, Manchester - Liverpool, London - Edinburgh

---

**Infrastructure Improvements:**

- **Conversion 1992**
- **Conversion 2006**
- **Conversion 2008**
- **New Build 2000**
- **New Build 2013**
- **New Build 2016**
- **New Build 2018**

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**Electrification Type:**

- **New Build**: 2000, 2013, 2016, 2018
Appendix B  UK Dual Voltage Areas

A number of UK locations have dual voltage electrification, and their stray current mitigation measures are summarised below.\footnote{\textit{“Electrification Infrastructure – Reducing Whole Life Cost: DC Stray Currents"}, M. Sigrist; 2014; Network Rail}

AC Isolation Transformers

AC isolation transformers (section 9.11.1) are fitted at:

- 25kV AC OLE on ECML to 750V DC 3rd rail on Moorgate Branch at Drayton Park;
- 2x25kV AC OLE on High Speed 1 to 750V DC 3rd rail on mainline at Dollands Moor freight yard, Ashford, Ebsfleet and Fawkham Junction;
- 25kV AC OLE on WCML to 750V DC 3rd rail on North London Line (NLL) at Primrose Hill;
- 25kV AC OLE on NLL to 750V DC 3rd rail NLL at Acton Central;
- 25kV AC OLE on West London Line (WLL) and North Pole Depot to 750V DC 3rd rail WLL at Scrubs Lane;
- 25kV AC OLE on NLL to 660V DC 4th rail on London Underground at Willesden Junction.

DC Contactors

DC Contactors (section 9.11.2) are fitted at:

- 25kV AC OLE on Thameslink to 750V DC 3rd rail on Thameslink at Ludgate Cellars.

Non-linear Resistors

Non-linear resistors (section 9.11.1) are fitted at:

- 25kV AC OLE on NLL to 750V DC 3rd rail on East London Line at Dalston to Highbury & Islington;

DC Stray Current Collection Mat, AC Foundation Insulation

- Adjacent 25kV AC OLE and 750V DC OLE on Manchester Metrolink at Manchester Victoria.

No Specific Measures

No specific measures are believed to be taken at:

- Shared and adjacent 25kV AC OLE on WCML and 660V DC 3rd/4th rail on London Overground between Euston and Watford Junction;
• Adjacent 25kV AC OLE on London Tilbury & Southend (LT&S) and 660V DC 4th rail on London Underground between Bromley by Bow and Upminster;
• 25kV AC OLE on WCML to 750V DC 3rd rail on Merseyrail at Hunts Cross West Junction;
• Adjacent 25kV AC OLE on GWML to 660V DC 4th rail on London Underground between Paddington and Royal Oak and at Ealing Broadway;
• Adjacent 25kV AC OLE on GWML and 750V DC 3rd rail at Reading;
• Adjacent 25kV AC OLE on ECML and 750V DC 3rd rail on NLL at Canonbury West Junction.
• Adjacent 25kV AC OLE on LT&S and 750V DC 3rd rail on Docklands Light Railway (DLR) between Christian Street Junction and Limehouse.
• Adjacent 25kV AC OLE on mainline and 750V DC OLE on Midland Metro at Birmingham New Street/Stephenson Street.
• Adjacent 25kV AC OLE on ECML and 1500V DC OLE on Tyne & Wear Metro at Manors, Chillingham Road/Heaton and Benton.

To Be Confirmed

The following interfaces are to be confirmed:
• Adjacent 25kV AC OLE on Edinburgh & Glasgow (E&G) and 750V DC OLE on Edinburgh Tram between Haymarket and Edinburgh Park;
• Adjacent 25kV AC OLE and 750V DC OLE on Manchester Metrolink at Manchester Piccadilly, Deansgate, Manchester Airport;
• Adjacent 25kV AC OLE on Crossrail and 750V DC 3rd rail on mainline between Woolwich and Abbey Wood;
• Adjacent 25kV AC OLE on GEML and 660V DC 4th rail on London Underground at Stratford;
• Adjacent 25kV AC OLE on GEML and 750V DC 3rd rail on DLR between Bow Junction and Stratford.
Appendix C  UK Pantograph Types

This appendix describes the pantographs which are operational in the UK today, together with those which have been used on UK 25kV infrastructure in the past. Operational speeds quoted are maxima permitted in the UK – the pantograph may be used at higher speeds in other countries.

The details below are collated from a variety of sources. Individual train operators will often modify pantographs based on in-service experience, so these should be considered broad categories only.
Figure 278: AEI Cross-arm pantograph

<table>
<thead>
<tr>
<th>AEI Cross-arm Pantograph</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>25kV AC</td>
</tr>
<tr>
<td>Use:</td>
<td>Mainline</td>
</tr>
<tr>
<td>In UK Since:</td>
<td>1960</td>
</tr>
<tr>
<td>Max Speed:</td>
<td>177kph</td>
</tr>
<tr>
<td>Arm:</td>
<td>Two crossed diamond</td>
</tr>
<tr>
<td>No. of Strips:</td>
<td>2</td>
</tr>
<tr>
<td>Strip Spacing:</td>
<td>TBC</td>
</tr>
<tr>
<td>Linkage Type:</td>
<td>Provided by twin arms</td>
</tr>
<tr>
<td>Suspension:</td>
<td>Primary/ secondary</td>
</tr>
<tr>
<td>Secondary Suspension Type:</td>
<td>Twin plungers</td>
</tr>
<tr>
<td>Secondary Travel:</td>
<td>None?</td>
</tr>
<tr>
<td>Aerofoils:</td>
<td>None</td>
</tr>
<tr>
<td>Strip Material:</td>
<td>TBC</td>
</tr>
<tr>
<td>Auto-Drop Device?</td>
<td>TBC</td>
</tr>
<tr>
<td>Over Height Drop?</td>
<td>TBC</td>
</tr>
<tr>
<td>Horn Mount:</td>
<td>Integral with carbons</td>
</tr>
<tr>
<td>Horn Type:</td>
<td>Live</td>
</tr>
<tr>
<td>Head Profile¹¹⁰:</td>
<td>BR Profile</td>
</tr>
<tr>
<td>---------------</td>
<td>------------</td>
</tr>
<tr>
<td>TSI Compliant:</td>
<td>No</td>
</tr>
<tr>
<td>Fitted To:</td>
<td>Originally fitted to class 86, 87. All now replaced.</td>
</tr>
<tr>
<td>Notes:</td>
<td>No longer in use. All remaining pans are unserviceable on preserved rolling stock.</td>
</tr>
</tbody>
</table>

¹¹⁰ “BR profile” denotes profile as per BS EN 50367:2012+A1:2016 figure B.6; “Europan” denotes profile as per BS EN 50367 Fig. A.6; “HS1 profile” denotes profile as per BS EN 50367 Fig. B.3
Figure 279: Stone-Faiveley AM/BR pantograph with Brecknell Willis Head

<table>
<thead>
<tr>
<th>Stone-Faiveley AM/BR Pantograph</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Voltage</strong></td>
</tr>
<tr>
<td><strong>Use:</strong></td>
</tr>
<tr>
<td><strong>In UK Since:</strong></td>
</tr>
<tr>
<td><strong>Max Speed:</strong></td>
</tr>
<tr>
<td><strong>Arm:</strong></td>
</tr>
<tr>
<td><strong>No. of Strips:</strong></td>
</tr>
<tr>
<td><strong>Strip Spacing:</strong></td>
</tr>
<tr>
<td><strong>Linkage Type:</strong></td>
</tr>
<tr>
<td><strong>Suspension:</strong></td>
</tr>
<tr>
<td><strong>Secondary Suspension Type:</strong></td>
</tr>
<tr>
<td><strong>Secondary Travel:</strong></td>
</tr>
<tr>
<td><strong>Aerofoils:</strong></td>
</tr>
<tr>
<td><strong>Strip Material:</strong></td>
</tr>
<tr>
<td><strong>Auto-Drop Device?</strong></td>
</tr>
<tr>
<td><strong>Over Height Drop?</strong></td>
</tr>
<tr>
<td><strong>Horn Mount:</strong></td>
</tr>
<tr>
<td><strong>Horn Type:</strong></td>
</tr>
<tr>
<td>Head Profile:</td>
</tr>
<tr>
<td>-------------</td>
</tr>
<tr>
<td>TSI Compliant:</td>
</tr>
<tr>
<td>Fitted To:</td>
</tr>
<tr>
<td>Notes:</td>
</tr>
</tbody>
</table>
Figure 280: Brecknell Willis HS-A pantograph

<table>
<thead>
<tr>
<th>Brecknell Willis HS-A Pantograph</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Voltage</strong></td>
<td>25kV AC</td>
</tr>
<tr>
<td><strong>Use:</strong></td>
<td>Mainline</td>
</tr>
<tr>
<td><strong>In UK Since:</strong></td>
<td>1980</td>
</tr>
<tr>
<td><strong>Max Speed:</strong></td>
<td>225kph</td>
</tr>
<tr>
<td><strong>Arm:</strong></td>
<td>Single</td>
</tr>
<tr>
<td><strong>No. of Strips:</strong></td>
<td>2</td>
</tr>
<tr>
<td><strong>Strip Spacing:</strong></td>
<td>300mm?</td>
</tr>
<tr>
<td><strong>Linkage Type:</strong></td>
<td>Internal 4th bar attached to chain at knuckle, internal bar link to head</td>
</tr>
<tr>
<td><strong>Suspension:</strong></td>
<td>Primary/ secondary</td>
</tr>
<tr>
<td><strong>Secondary Suspension Type:</strong></td>
<td>Torsion bar on trailing arm</td>
</tr>
<tr>
<td><strong>Secondary Travel:</strong></td>
<td>65mm</td>
</tr>
<tr>
<td><strong>Aerofoils:</strong></td>
<td>On head</td>
</tr>
<tr>
<td><strong>Strip Material:</strong></td>
<td>TBC</td>
</tr>
<tr>
<td><strong>Auto-Drop Device?</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Over Height Drop?</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Horn Mount:</strong></td>
<td>Integral with carbons</td>
</tr>
<tr>
<td><strong>Horn Type:</strong></td>
<td>Live</td>
</tr>
<tr>
<td><strong>Head Profile:</strong></td>
<td>BR profile</td>
</tr>
<tr>
<td>TSI Compliant:</td>
<td>No</td>
</tr>
<tr>
<td>Fitted To:</td>
<td>Class 87, 89, 90, 91, 92, 317, 319, 320, 321, 322, 323, 325, 332, 333, 370, 390</td>
</tr>
<tr>
<td>Notes:</td>
<td>Also known as BW high speed</td>
</tr>
</tbody>
</table>
Figure 281: Brecknell Willis HS-P Mark 1 pantograph

<table>
<thead>
<tr>
<th>Brecknell Willis HS-P Mark 1 Pantograph</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Voltage</strong></td>
</tr>
<tr>
<td><strong>Use:</strong></td>
</tr>
<tr>
<td><strong>In UK Since:</strong></td>
</tr>
<tr>
<td><strong>Max Speed:</strong></td>
</tr>
<tr>
<td><strong>Arm:</strong></td>
</tr>
<tr>
<td><strong>No. of Strips:</strong></td>
</tr>
<tr>
<td><strong>Strip Spacing:</strong></td>
</tr>
<tr>
<td><strong>Linkage Type:</strong></td>
</tr>
<tr>
<td><strong>Suspension:</strong></td>
</tr>
<tr>
<td><strong>Secondary Suspension Type:</strong></td>
</tr>
<tr>
<td><strong>Secondary Travel:</strong></td>
</tr>
<tr>
<td><strong>Aerofoils:</strong></td>
</tr>
<tr>
<td><strong>Strip Material:</strong></td>
</tr>
<tr>
<td><strong>Auto-Drop Device?</strong></td>
</tr>
<tr>
<td><strong>Over Height Drop?</strong></td>
</tr>
<tr>
<td><strong>Horn Mount:</strong></td>
</tr>
<tr>
<td><strong>Horn Type:</strong></td>
</tr>
<tr>
<td><strong>Head Profile:</strong></td>
</tr>
<tr>
<td><strong>TSI Compliant:</strong></td>
</tr>
<tr>
<td>--------------------</td>
</tr>
<tr>
<td><strong>Fitted To:</strong></td>
</tr>
<tr>
<td><strong>Notes:</strong></td>
</tr>
</tbody>
</table>
Figure 282: Brecknell Willis HS-P Mark 2 pantograph

<table>
<thead>
<tr>
<th>Brecknell Willis HS-P Mark 2 Pantograph</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>25kV AC</td>
</tr>
<tr>
<td>Use</td>
<td>Mainline</td>
</tr>
<tr>
<td>In UK Since</td>
<td>2005</td>
</tr>
<tr>
<td>Max Speed</td>
<td>175kph</td>
</tr>
<tr>
<td>Arm</td>
<td>Single</td>
</tr>
<tr>
<td>No. of Strips</td>
<td>2</td>
</tr>
<tr>
<td>Strip Spacing</td>
<td>300mm</td>
</tr>
<tr>
<td>Linkage Type</td>
<td>Internal 4th bar attached to chain at knuckle, internal bar link to head</td>
</tr>
<tr>
<td>Suspension</td>
<td>Primary/ secondary</td>
</tr>
<tr>
<td>Secondary Suspension Type</td>
<td>Twin plungers</td>
</tr>
<tr>
<td>Secondary Travel</td>
<td>40mm</td>
</tr>
<tr>
<td>Aerofoils</td>
<td>On knuckle</td>
</tr>
<tr>
<td>Strip Material</td>
<td>TBC</td>
</tr>
<tr>
<td>Auto-Drop Device?</td>
<td>Yes</td>
</tr>
<tr>
<td>Over Height Drop?</td>
<td>Yes</td>
</tr>
<tr>
<td>Horn Mount</td>
<td>Integral with head frame</td>
</tr>
<tr>
<td>Horn Type</td>
<td>Live</td>
</tr>
<tr>
<td>Head Profile</td>
<td>BR profile</td>
</tr>
<tr>
<td>TSI Compliant:</td>
<td>Yes</td>
</tr>
<tr>
<td>-------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>Fitted To:</td>
<td>Class 88, 345, 350/1, 385, 387, 700</td>
</tr>
<tr>
<td>Notes:</td>
<td>Also known as BW High Speed Plunger, Desiro Mk2</td>
</tr>
</tbody>
</table>
Figure 283: Brecknell Willis HS-P Mark 2 “Donuts” pantograph

<table>
<thead>
<tr>
<th>Brecknell Willis HS-P Mark 2 “Donuts” Pantograph</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Voltage</strong></td>
<td>25kV AC</td>
</tr>
<tr>
<td><strong>Use:</strong></td>
<td>Mainline</td>
</tr>
<tr>
<td><strong>In UK Since:</strong></td>
<td>2005</td>
</tr>
<tr>
<td><strong>Max Speed:</strong></td>
<td>175kph</td>
</tr>
<tr>
<td><strong>Arm:</strong></td>
<td>Single</td>
</tr>
<tr>
<td><strong>No. of Strips:</strong></td>
<td>2</td>
</tr>
<tr>
<td><strong>Strip Spacing:</strong></td>
<td>300mm</td>
</tr>
<tr>
<td><strong>Linkage Type:</strong></td>
<td>Internal 4th bar attached to chain at knuckle, internal bar link to head</td>
</tr>
<tr>
<td><strong>Suspension:</strong></td>
<td>Primary/ secondary</td>
</tr>
<tr>
<td><strong>Secondary Suspension Type:</strong></td>
<td>Twin plungers</td>
</tr>
<tr>
<td><strong>Secondary Travel:</strong></td>
<td>40mm</td>
</tr>
<tr>
<td><strong>Aerofoils:</strong></td>
<td>On knuckle</td>
</tr>
<tr>
<td><strong>Strip Material:</strong></td>
<td>TBC</td>
</tr>
<tr>
<td><strong>Auto-Drop Device?</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Over Height Drop?</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Horn Mount:</strong></td>
<td>Integral with head frame</td>
</tr>
<tr>
<td><strong>Horn Type:</strong></td>
<td>Live</td>
</tr>
<tr>
<td><strong>Head Profile:</strong></td>
<td>BR profile</td>
</tr>
<tr>
<td><strong>TSI Compliant:</strong></td>
<td>Yes</td>
</tr>
<tr>
<td>Fitted To:</td>
<td>Class 387/1</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------</td>
</tr>
<tr>
<td>Notes:</td>
<td>Donuts (toroids) are fitted to reduce electrical stress for arcing to the roof in low wire height areas</td>
</tr>
</tbody>
</table>
Figure 284: Brecknell Willis HSX-250 pantograph

<table>
<thead>
<tr>
<th>Brecknell Willis HSX-250 Pantograph</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Voltage</strong></td>
</tr>
<tr>
<td><strong>Use:</strong></td>
</tr>
<tr>
<td><strong>In UK Since:</strong></td>
</tr>
<tr>
<td><strong>Max Speed:</strong></td>
</tr>
<tr>
<td><strong>Arm:</strong></td>
</tr>
<tr>
<td><strong>No. of Strips:</strong></td>
</tr>
<tr>
<td><strong>Strip Spacing:</strong></td>
</tr>
<tr>
<td><strong>Linkage Type:</strong></td>
</tr>
<tr>
<td><strong>Suspension:</strong></td>
</tr>
<tr>
<td><strong>Secondary Suspension Type:</strong></td>
</tr>
<tr>
<td><strong>Secondary Travel:</strong></td>
</tr>
<tr>
<td><strong>Aerofoils:</strong></td>
</tr>
<tr>
<td><strong>Strip Material:</strong></td>
</tr>
<tr>
<td><strong>Auto-Drop Device?</strong></td>
</tr>
<tr>
<td><strong>Over Height Drop?</strong></td>
</tr>
<tr>
<td><strong>Horn Mount:</strong></td>
</tr>
<tr>
<td><strong>Horn Type:</strong></td>
</tr>
<tr>
<td><strong>Head Profile:</strong></td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td><strong>TSI Compliant:</strong></td>
</tr>
<tr>
<td><strong>Fitted To:</strong></td>
</tr>
</tbody>
</table>
| **Notes:** | }
Figure 285: Faiveley GPU™ pantograph

<table>
<thead>
<tr>
<th>Faiveley GPU Pantograph</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>25kV AC, 1.5 kV DC</td>
</tr>
<tr>
<td>Use</td>
<td>High Speed</td>
</tr>
<tr>
<td>In UK Since</td>
<td>1993</td>
</tr>
<tr>
<td>Max Speed</td>
<td>300kph (AC)</td>
</tr>
<tr>
<td></td>
<td>270kph (DC)</td>
</tr>
<tr>
<td>Arm</td>
<td>Single</td>
</tr>
<tr>
<td>No. of Strips</td>
<td>2</td>
</tr>
<tr>
<td>Strip Spacing</td>
<td>TBC</td>
</tr>
<tr>
<td>Linkage Type</td>
<td>External bar links</td>
</tr>
<tr>
<td>Suspension</td>
<td>Primary/ secondary/ tertiary</td>
</tr>
<tr>
<td>Secondary Suspension Type</td>
<td>Single plunger (secondary) twin plungers (tertiary)</td>
</tr>
<tr>
<td>Secondary Travel</td>
<td>150</td>
</tr>
<tr>
<td>Aerofoils</td>
<td>On head</td>
</tr>
<tr>
<td>Strip Material</td>
<td>TBC</td>
</tr>
</tbody>
</table>

GPU stands for “Grand Plongeur Unique” (large, single plunger)
<table>
<thead>
<tr>
<th><strong>Auto-Drop Device?</strong></th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Over Height Drop?</strong></td>
<td>No – mechanical height limit device provided</td>
</tr>
<tr>
<td><strong>Horn Mount:</strong></td>
<td>To secondary-sprung head</td>
</tr>
<tr>
<td><strong>Horn Type:</strong></td>
<td>Insulated</td>
</tr>
<tr>
<td><strong>Head Profile:</strong></td>
<td>HS1 profile</td>
</tr>
<tr>
<td><strong>TSI Compliant:</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Fitted To:</strong></td>
<td>Class 373 Eurostar</td>
</tr>
<tr>
<td><strong>Notes:</strong></td>
<td>Captive to HS1 route only, now being withdrawn from service</td>
</tr>
</tbody>
</table>
Figure 286: Faiveley CX PG monoband pantograph

<table>
<thead>
<tr>
<th>Faiveley CX PG Monoband Pantograph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
</tr>
<tr>
<td>Use:</td>
</tr>
<tr>
<td>In UK Since:</td>
</tr>
<tr>
<td>Max Speed:</td>
</tr>
<tr>
<td>Arm:</td>
</tr>
<tr>
<td>No. of Strips:</td>
</tr>
<tr>
<td>Strip Spacing:</td>
</tr>
<tr>
<td>Linkage Type:</td>
</tr>
<tr>
<td>Suspension:</td>
</tr>
<tr>
<td>Secondary Suspension Type:</td>
</tr>
<tr>
<td>Secondary Travel:</td>
</tr>
<tr>
<td>Aerofoils:</td>
</tr>
<tr>
<td>Strip Material:</td>
</tr>
<tr>
<td>Auto-Drop Device?:</td>
</tr>
<tr>
<td>Over Height Drop?:</td>
</tr>
<tr>
<td>Horn Mount:</td>
</tr>
<tr>
<td>Horn Type:</td>
</tr>
<tr>
<td>Head Profile:</td>
</tr>
<tr>
<td>-------------</td>
</tr>
<tr>
<td>TSI Compliant:</td>
</tr>
<tr>
<td>Fitted To:</td>
</tr>
<tr>
<td>Notes:</td>
</tr>
</tbody>
</table>
Figure 287: Faiveley CX NG pantograph

<table>
<thead>
<tr>
<th>Faiveley CX NG Pantograph</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Voltage</strong></td>
</tr>
<tr>
<td><strong>Use:</strong></td>
</tr>
<tr>
<td><strong>In UK Since:</strong></td>
</tr>
<tr>
<td><strong>Max Speed:</strong></td>
</tr>
<tr>
<td><strong>Arm:</strong></td>
</tr>
<tr>
<td><strong>No. of Strips:</strong></td>
</tr>
<tr>
<td><strong>Strip Spacing:</strong></td>
</tr>
<tr>
<td><strong>Linkage Type:</strong></td>
</tr>
<tr>
<td><strong>Suspension:</strong></td>
</tr>
<tr>
<td><strong>Secondary Suspension Type:</strong></td>
</tr>
<tr>
<td><strong>Secondary Travel:</strong></td>
</tr>
<tr>
<td><strong>Aerofoils:</strong></td>
</tr>
<tr>
<td><strong>Strip Material:</strong></td>
</tr>
<tr>
<td><strong>Auto-Drop Device?</strong></td>
</tr>
<tr>
<td><strong>Over Height Drop?</strong></td>
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<tr>
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<tr>
<td>Fitted To:</td>
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**Brecknell Willis High Reach Pantograph**

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<tr>
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<td><strong>Linkage Type</strong></td>
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Figure 289: Schunk SB pantograph

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UK OLE Types

107 HDCu

11000

AT
AT
AT
AT
FT
AT
FT
AT
FT
AT
AT
FT
AT
AT
AT
AT
AT
AT
AT
AT
AT

107 HDCu
120 CuAg
120 CuAg
107 HDCu
107 CuCd
107 HDCu
107 CuCd
107 HDCu
107 CuCd
107 CuSn (0.4)
107 Cu-Mg
107 CuSn (0.4)
107 CuCd
150 HDCu
?
120 CuAg
120 CuAg
150 HDCu
107 CuAg
120 CuAg
120 CuAg

11910
11900
11900
11000
11180
11000
11180
11000
11180
11000
11000
?
18000
20200
?
11900
14000
20000
11230
13200
7500

AT

120 CuSn

AT
AT
FT
AT
AT
AT
AT

120 CuAg
107 CuAg
107 CuAg
107 CuAg
107 CuSn
120 CuAg
120 CuAg

N/A

None

120 CuAg

Rigid Overhead Conductor Bar

N/A

None

150 HDCu?

0

0

No

-

Sagged Simple AT (heavy catenary)
Sagged Simple AT (light catenary)

Sagged Simple

AT

150 HDCu
150 HDCu

12000
12000

2696
2696

Yes
Yes

37/1.5 BzII
19/2.1 BzII

Mk 3A-00-FT/T

39 Mark 3a
40

Mk 3A-01-AT-S
Mk 3A-02-AT-S

41

Mk 3A-03-AT-S

Sagged Stitched Simple AT

42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Mk 3A-04-AT-TW
N/A
N/A
Mk 3B-01-AT-S
Mk 3B-00-FT-S
Mk 3B-00-AT-T
Mk 3B-00-FT-T
Mk 3C-00-AT-S
Mk 3C-00-FT-S

Tramway AT
Sagged Simple AT UK1 upgrade (for 200kph)
Sagged Simple AT UK1 upgrade (for 225kph)
Sagged Simple AT
Simple FT
Tramway AT
Tramway FT
Sagged Simple AT
Simple FT
Sagged Simple AT
Sagged Simple AT (modified)
Simple FT
Compound AT
Simple AT
Sagged? Simple AT
Sagged Simple AT (for 200kph)
Sagged Simple AT (for 225kph)
Sagged Simple AT
Simple AT
Sagged Simple AT
Sagged Simple AT
Sagged Simple AT

Sagged Simple

Sagged Simple AT
Sagged Simple AT
Sagged Simple FT
Sagged Simple AT
Sagged Simple AT
Sagged Simple AT
Sagged Simple AT

Sagged Simple
Sagged Simple
Sagged Simple
Sagged Simple
Sagged Simple
Sagged Simple
Sagged Simple

Rigid Overhead Conductor Bar

Mark 3d

N/A

Mark 4
Mark 5
Channel Tunnel

N/A
Mk 5-00-AT-S
N/A

UK1 standalone

N/A

High Speed One
SICAT

N/A
SICAT SA

GEFF

61 Series 1
62
63 Series 2
64
65
66
UK Master Series
67
68

Series 2(120)
Series 2(107)
Series 2(FT)
UKMS100
UKMS100-Sn
UKMS125
UKMS140

69 F+F ROCS
Alstom Cariboni
70
ROCS
71
Alstom Cariboni
72

Cariboni FOC

Simple FT (1 x simple equipment splits into 2 x tramway)
Sagged Simple AT (Mk3b tensions)
Sagged Simple AT (supertensioned)

Notes
§ Cantilever/Headspan
¢ Catenary tension lengths longer than aux/cw tension lengths - typically, one cat covers 3 aux/cws
ML = mainline
RML = reduced mainline

N/A
Yes
No
N/A
N/A
No
N/A
Yes
Yes

19/2.1 HDCu
19/2.1 HDCu
5/2/3.95 AWAC
5/2/3.95 AWAC
5/2/3.95 AWAC
5/2/3.95 AWAC
5/2/3.95 AWAC

N
11100
8630
11000
8630
8630
11000
11160

lb
2494
1939
2472
1939
1939
2472
2507

2472

Yes

5/2/3.95 AWAC

11000

2472

2676
2674
2674
2472
2512
2472
2512
2472
2512
2472
2472
?
4045
4539
?
2674
3146
4494
2523
2966
1685

N/A
Yes
19/2.1 CuCd
Yes
19/2.1 CuCd
Yes 5/2/3.95 AWAC
No 5/2/3.95 AWAC
N/A
N/A
Yes
19/2.1 HDCu
No
19/2.1 CuCd
Yes
19/2.1 Bz
Yes
19/2.1 Bz
No
19/2.1 Bz
Yes 19/3.39 AWAC
Yes
37/2.5 HDCu
Yes?
?
Yes
19/2.1 CuCd
Yes
19/2.1 CuCd
Yes
37/1.5 Bz
19/2.1 BzII
Yes
19/2.1 BzII
Yes
19/2.1 BzII

8560
8560
11000
8630
11000
8630
11000
11000
?
24000
20720
?
8560
8560
14000
11230
12000
10000

16500

3708

Yes

19/2.1 BzII

14000
11000
11000
11000
11000
15000
16500

3146
2472
2472
2472
2472
3372
3708

Yes
Yes
Yes
Yes
Yes
Yes
Yes

19/2.1 BzII
19/2.1 BzII
19/2.1 BzII
19/2.1 BzII
19/2.1 BzII
19/2.1 BzII
19/2.1 BzII

0

0

No

-

2 of 6

Yes

Tension @
setup temp

N
-

lb
-

2250
11000
-

-

-

-

-

-

-

-

-

12000
12000

2696
2696

Linespeed
System Height

AT

38

Tension @ setup Aux. Catenary or
Stitch Wire
temp
Cross Section
(mm²) &
Material

lb
2005
2512
2512
2006
2512
2006
2512
2512
2x2512
2472
2507

Suspension
Sagged Simple
Simple
Tramway
Sagged Simple
Simple
Tramway
Tramway
Simple
Tramway
Sagged Simple
Sagged Simple
Sagged Stitched
Simple
Tramway
Sagged Simple
Sagged Simple
Sagged Simple
Simple
Tramway
Tramway
Sagged Simple
Simple
Sagged Simple
Sagged Simple
Simple
Compound
Simple
Sagged? Simple
Sagged Simple
Sagged Simple
Sagged Simple
Simple
Sagged Simple
Sagged Simple

Cross Section
(mm²) &
Material

N
8925
11180
11180
8930
11180
8930
11180
11180
2x11180
11000
11160

Subtype
Sagged Simple AT
Simple FT
Tramway
Sagged Simple AT
Simple FT
Tramway AT
Tramway FT

Presag?

Cross Section
(mm²) &
Material
107 HDCu
107 CuCd
107 CuCd?
107 HDCu
107 CuCd
107 HDCu
107 CuCd
107 CuCd
2x107 CuCd
107 HDCu
107 HDCu

Designation
?
?
?
Mk 3A-00-AT-S
Mk 3A-00-FT-S
Mk 3A-00-AT-T
Mk 3A-00-FT-T

Mark 3c

Catenary

AT
FT
FT?
AT
FT
AT
FT
FT
FT
AT
AT

Type
31
32 Mark 3
33
34
35
36
37

Mark 3b

Tension @ setup
temp

Tensioning

No.

Contact Wire

15/12/2018

TSI
Comp
?
No
No
No

mph
110
64
20
110
60
?
18
?
?
110
125

kph
175
100
30
175
95
?
30
?
?
175
200

505

125

200

2472
-

1400
1200
-

60
125
140
125
60
25
25
125
60
125
?
?
155
100
100
125
140
189
100
100
60

95
200
225
200
95
40
40
200
95
200
?
?
245
160
160
200
225
300
160
160
100

-

-

140

225

-

1400
1400
1400
1300
1300
1300
1300

100
100
60
100
100
125
140

160
160
100
160
160
200
225

-

-

-

?

?

-

-

-

-

?

?

Yes

-

-

-

?

60

100

Yes?

1923
1923
2472
1939
2472
1939
2472
2472
?
5393
4656
?
1923
1923
3146
2523
2696
2247

4mm Stainless
Steel
19/3.39 AWAC
-

13000

2921

12000
11000
11000
11000
11000
12000
13000

2696
2472
2472
2472
2472
2696
2921

-

1400
-

1400

900/1400§
1400
900/1400§
900/1400§
900/1400§
900/1400§
?
1100-1400
?
?

No

No

No
No
No
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Yes
Yes
Yes
Yes
Yes
Yes
Yes


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Notes:
- C - Cantilever/Headspan
- ML - ML = mainline
- RML = reduced mainline
- * = reduced mainline
- TSI Comp - TSI Comp.
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**Notes:**
- A/B/C = Headshunts
- Reduced tension Tramway FT (1 x heavy equipment splits into 2 x light)
- Gas Factory Jct - Bow Jct
- Manchester - Sheffield (via Wath - now curtailed to Anstboro - Hadfield)
- Liverpool St - Shienfield; Christian St Jct - Gas Factory Jct; Manchester - Sheffield (via Wath - now curtailed to Anstboro - Hadfield)
- London Euston - Waverley Jct; Crewe - Liverpool; Groby - Manchester; Crewe - Manchester; Rugby - Stafford via Birmingham: Roade - Rugby via Northampton; Glasgow suburban stage 1; Chineham St Jct - Sholing; Barking - Purley via Grove; Chelmsford - Galteshur; Colchester - Clacton & Walton; Bethnal Green - Bishop's Stortford, Hertford East, Enfield & Chingford.
- 1500V DC
- 6.25kV AC
- 25kV AC
- 1500V DC
- 25kV AC
- 25kV AC

**Locations:**
- Shenfield - Witham; Shenfield - Southend
- Liverpool St - Shienfield; Christian St Jct - Gas Factory Jct; Manchester - Sheffield (via Wath - now curtailed to Anstboro - Hadfield)
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Notes:
- ML = mainline
- RL = relief mainline
- 1 1/2 Loop = loop
- Conversion = lengths - typically, one cat covers 3 aux/cw
## Table of Figures

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