



ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)
OFFICIAL MASTER'S DEGREE IN RAILWAY SYSTEMS

DETAILED DESIGN OF THE CATENARY IN THE EXTENSION OF A TRAMWAY SYSTEM IN WOLVERHAMPTON, UK

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Madrid
July, 2015

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Official Master's Degree in Railway Systems (MSF), 2014-2015

Title: Detailed design of the catenary in the extension of a tramway system in Wolverhampton, UK

ABSTRACT

The design of a catenary is a complex process, where all the electrical, geometrical and mechanical characteristics of the line, the trains and the surroundings should be taken into account. For this project, the following had to be considered: a proposed layout, the applicable regulations for the design of this type of lines in the UK and the characteristics of the existing line, because the new one had to be compatible with it.

Once the parameters of the existing line and the applicable regulation were studied, electrical and mechanical calculations have been accomplished. The long-term operational load and the short-circuit current have been calculated in order to select the appropriate wires (materials, cross sections, etc.). The positions of the supports have been chosen according to the maximum span length that could be achievable, which depended on multiple parameters, such as the tensile forces, the wind load and the radius of the curves. Once the positions were chosen, it should be demonstrated that the loads do not exceed the maximum permitted on wires and, where applicable, on poles. Then, the geometry of the cross-span arrangements, the reaction forces at the supports and the moments on the base of the poles have been calculated, in order to define the position and size of every support, attachment or foundation.

There are some key risks to this OLE design: track alignment changes, unsuitability of buildings for fixing to and inability to obtain the permission or statutory powers to make fixings to the buildings identified in the layout.

This project has provided a bus, rail and tram interchange to the city of Wolverhampton, facilitating the intermodal transport.



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Abbreviations

Abbreviation	Meaning
DC	Direct Current
EMC	Electro-Magnetic Compatibility
EMI	Electro-Magnetic Interferences
EPR-CSP	Composite ethylene propylene rubber chlorosulphonated polyethylene
OLE	Overhead Line Equipment
ORR	Office of Rail Regulation
VLD	Voltage Limiting Device
WCCE	Wolverhampton City Centre Extension
WIP	Wolverhampton Interchange Project



Chapter 1 INTRODUCTION

The design of the overhead contact line in a railway system should be done in order to achieve the best current-collection possible, either if it is a tramway system, a suburban system or a longer distance line (commuters, regional trains and medium or long distance). The goodness of this current-collection depends on the particular characteristics of the infrastructure, such as the gauge, the tolerances, etc. and also on the speed of the vehicles and their geometry. There are other factors to be considered, such as safety requirements and structural isolation distances (CARN14).

As a result, the design of the catenary is a complex process, where all the electrical, geometrical and mechanical characteristics should be taken into account. The present study, additionally, has been influenced by an existing line. This fact affects strongly the design, because it has to be ensured that the new system is perfectly compatible with the existing one.

The different tasks that have been carried out for this project are given in *Chapter 2*. These include the study of the characteristics of the existing line, the establishment of design decisions and the distribution of the various supports (poles and building fixings) depending on the characteristics of the track and the surroundings. In *Chapter 3*, electrical and mechanical calculations have been conducted. Finally, *Chapter 4* collects the conclusions and contributions derived from the realization of this Master's Thesis.

1.1 OBJECTIVES

The purpose of this project is to design a catenary system for the prolongation of a tramway line in the United Kingdom. To that end, the following has to be considered: the proposed layout, the applicable regulations for the design of this type of lines in the UK and the characteristics of the existing line, because the new one must be compatible with it, as it was mentioned before. Besides, there are some risks that have to be taken into account when designing the line: the possibility that the proposed layout changes and the impossibility of using the identified supports (poles and building fixings). In order to accomplish the aforementioned, the following objectives have been proposed:



- Adequate selection of the parameters for designing the line, so that they comply with the regulations and they ensure that the new system is perfectly compatible with the existing one.
- Design of the catenary according to the proposed layout, the characteristics of the surroundings and the restrictions that may take place.
- Check that the mechanical and safety requirements of the line are complied.

1.2 TASKS

For the purpose of accomplishing the established objectives, the next tasks have been performed:

- Study of the parameters of the existing line and the regulation applicable to the design of the new tramway line.
- Establishment of the technical specifications that should be considered, conducting the required calculations for it.
- Design of the catenary, establishing the type of supports that should be used and their position, depending on the possibility of using building fixings or not, because this is the preferred type of support in the UK.
- Mechanical calculations of the catenary, considering the vertical and radial forces and the existence of wind or ice, in order to check that the supports can withstand the loads that can appear and that the values for the mid-span offset that are given in the technical specifications are not exceeded.
- Check that all the requirements are accomplished and, if necessary, modifications should be done until the requirements are fulfilled.



1.3 SCHEDULING

The next tasks schedule has been followed to meet the deadlines:

Table 1.1. Tasks schedule

	oct-14	nov-14	dec-14	jan-15	feb-15	mar-15	apr-15	may-15	jun-15
Study of the existing line and the applicable regulation									
Establishment of the technical specifications									
Design of the catenary									
Mechanical calculations of the catenary									
Checks and modifications									
Drafting of the project									

Chapter 2 DESIGN

2.1 INTRODUCTION

Since 1999, the *Midland Metro tram system* has been operating successfully, carrying passengers between *Birmingham Snow Hill* and *Wolverhampton St. George's Stop* (RAMO14). The development of the new line, the so-called *Wolverhampton City Centre Extension (WCCE)*, started in 2009. Its purpose is to link the rail station and the lately constructed bus station together, extending the existing Metro network (*Midland Metro Line One*). Therefore, the city will be provided with a bus, rail and tram interchange, facilitating the intermodal transport (RAMO15). It also involves the “closing” of the so-called *Wolverhampton City Center Loop (WCCL)*, as it can be appreciated in the following figure:



Figure 2.1. *Wolverhampton City Centre Loop*

The proposed line will extend 700 metres (m) approximately from *St. George's Tram Stop* to *Wolverhampton Rail Station*. It will run on street, beginning at *Bilston Street* and along *Piper's Row*, *Victoria Square* and *Railway Drive*. The *WCCE* will be twin track along *Piper's Row* and *Railway Drive*, and will be reduced to a single track as the *Rail Station* is reached. This is to allow trams to be turned back within the platform. There is also an extension of the single track beyond the end of the platform which is sufficient to accommodate two further trams, provided for service and emergency purposes only.

As part of the *WCCE*, two tram stops are proposed. One is located on *Piper's Row*, at the bus station, and the other at the *Rail Station*. The former comprises complementary north and southbound stop platforms incorporated within the footways on either side of the highway (RAMO14). The proposed scheme is shown in the next figure:

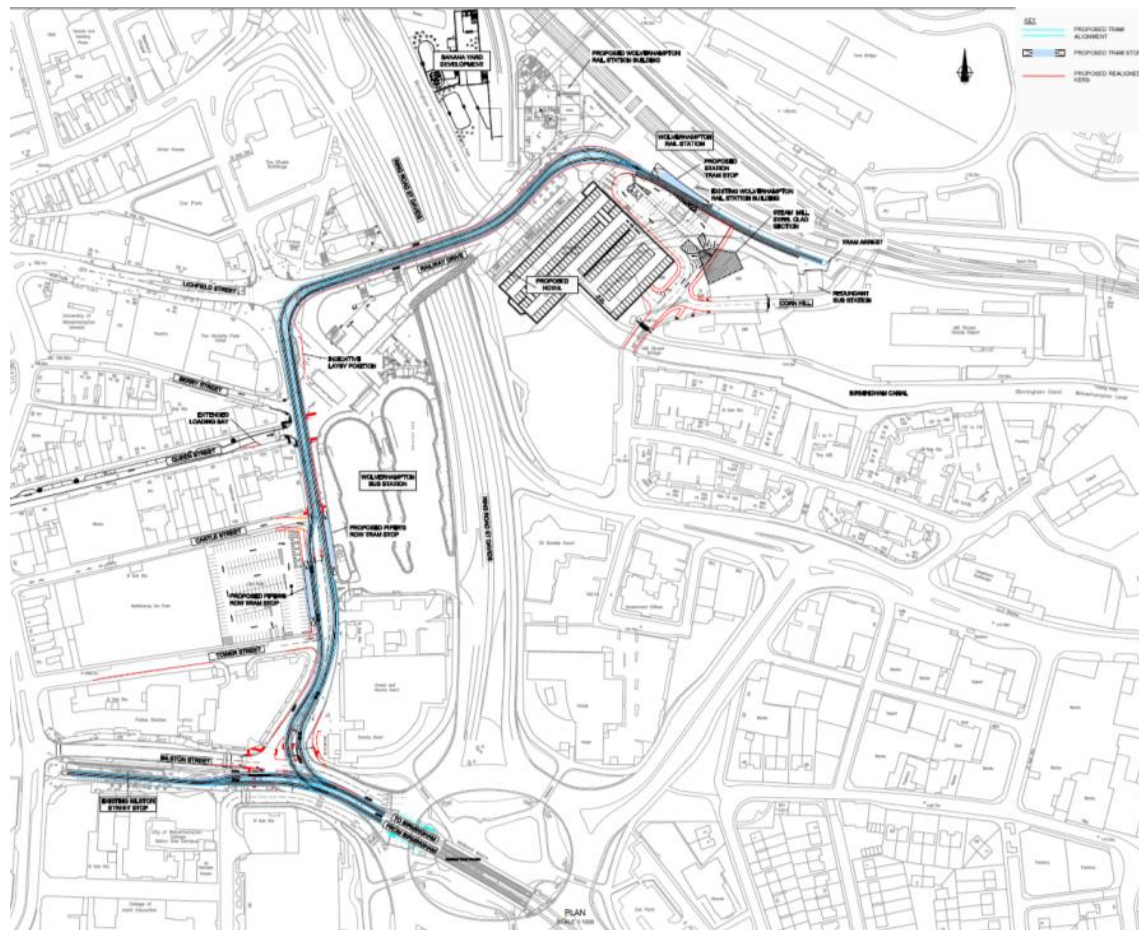


Figure 2.2. Outline proposal of Wolverhampton City Centre Extension



It should be mentioned that it is preferred to support the OLE with cross-span wires and building fixings, where possible. This fact affects considerably the design, as this type of solutions will always be sought. In turn, the possibility of using building fixings depends on:

- Their capability to withstand the loads that the OLE system may support.
- The ability to obtain statutory powers or the permission to make fixings to the buildings.

In cases where this solution is not possible, dedicated OLE poles or combined OLE and street lighting poles will be used, supporting cross-span wires, side-bridle arrangements and/or cantilever arms.

It is also important to highlight that the alignment offers multiple complexities, as changes in the gradient and reduced curvature of the track (up to 25 metres of radius). This also affects the design, as the position of the supports must ensure that the maximum span length, wire gradient and stagger are not exceeded.

2.2 EXISTING OLE SYSTEM DESCRIPTION

In 1999, the 20.7 km long Line 1 from *Birmingham Snow Hill* to *Wolverhampton St George's* was opened. The former *Great Western Railway* alignment was followed in much of the route.

The nominal traction power supply is 750 V DC. There are six substations along the route plus one substation to feed the depot at *Wednesbury*.

The OLE is generally supported by span wires. Fixings are to buildings and street lighting poles where possible. When not possible, dedicated poles are used.

Twin contact wires with an aerial parallel feeder, supported by poles and cantilever arms, are used for the off-street route. A single contact wire is used for the street-running and depot. There is no parallel feeder in this case.

For planned and emergency isolation of the OLE, isolating switches are provided along the route, in the substations and at intermediate points in trackside cabinets.

The electric traction current returns to the substations through the running rails (RAMO15).



2.2.1. Main and Ancillary Conductors

- Contact wire type
 - 150 mm² hard drawn copper.
- Contact wire tension
 - For the off-street route, constant tension controlled by gas tensioners.
 - For street-running and the depot, variable tension (fixed termination) with only one continuous tension length.
- Parallel feeder type
 - Stranded 19/2.8 mm (120 mm²) hard drawn copper, insulated with polyethylene coating.
- Traction feeder cable type
 - 240 mm² copper (EPR-CSP insulated) for the positive cable between substation and OLE.
 - 150 mm² copper (EPR-CSP insulated) for the negative cable between substation negative busbar and track.

2.2.2. Support and Suspension System Components

- Poles
 - Stepped circular hollow section. Steel tube galvanised inside and out. Attached to foundation via bolt cluster and flange plate.
 - Four types, type A for single track cantilevers; type C for single and double track cantilevers, for cross-spans and for anchors; type D for feeders at substations and trackside isolators and type E for combined street lighting with cross-spans.
- Cantilevered arms
 - Four types: short, medium, long and overlap. Galvanised steel.
- Insulators
 - Insulators are used as secondary insulation, between the cantilever arm and pole for cantilever supports, and are of composite material.
 - Primary insulation is provided by an insulated steady arm.



- Parafil rope
 - Flexible insulated rope used for many of the support assemblies. It provides secondary insulation.
- Fitting and clamps
 - Corrosion preventative material such as aluminium bronze, galvanised steel and stainless steel with bi-metallic connections where required. Electrical clamps are low resistance copper. Fittings to poles are by stainless steel tension bands, no drilling or welding to poles.
- Delta suspension
 - Two types: three-metre and street running. The former is used for auto-tensioned equipment and the street running is used for variable tension equipment. 6 mm parafil rope is used with aluminium bronze clamps and stainless steel terminations.
- Steady arms
 - Two types, plain and insulated. Where a plain arm is used, insulation is gained via a parafil sling connecting the arm to the cantilever or span wire. For variable tension areas where radial loads are small, steady arms are not used. Instead the delta suspension provides the registration.
- Span wires
 - 8 mm diameter parafil rope with aluminium bronze parafil terminals, aluminium anchor clamp, and nylon Cardan suspension clamps.
- Section insulators
 - Lightweight construction fitted with overlapping runners for uninterrupted current collection, bi-directional.

2.2.3. Foundations

- Concrete piles with three arrangements of bolt cluster. Four types of pile with varying load capacities.
 - Type A: 64 kNm bending load; 10.2 kN vertical load; 14.3 kN lateral load.
 - Type C: 133 kNm bending load; 20 kN vertical load; 19.9 kN lateral load.
 - Type D: 145 kNm bending load; 25 kN vertical load; 19.9 kN lateral load.
 - Type E: 145 kNm bending load; 25 kN vertical load; 19.9 kN lateral load.



2.2.4. Conductor Profile

- Contact wire height off-street running
 - Nominal design height is 4800 mm.
 - Minimum height is 3875 mm.
- Contact wire height street running
 - Normal minimum is 5800 mm.
 - Normal maximum is 6300 mm.
 - The contact wire is at a minimum height of 6550 mm across the junction of *Bilston Street* with the *Ring Road* at *Wolverhampton*.
 - In a failure of one pole or support the contact wire should not sag below 5200 mm above the highway. Spacing of existing poles suggests this criteria is not met and instead an alarm system may have been implemented whereby the Operator is alerted to an incident before safety of pedestrians is compromised. (Confirmation is sought as to whether this system was implemented and how successful it is).
- Contact wire grading
 - Maximum grading is 1:40 for all areas.
- Contact wire stagger
 - Nominal stagger is ± 200 mm.
- Parallel feeder height
 - At least 5200 mm above platform or rail level, whichever is the higher.
- Span length
 - Optimum span length is 45 m with a 3 m stitch.

2.2.5. Environmental

- Maximum design temperature is 35 °C.
- Minimum design temperature is -15 °C.
- Maximum design wind speed is 25 m/s.
- Maximum gust speed is 42 m/s.
- Maximum ice loading is 10 mm radial thickness at 25 m/s wind.



2.2.6. Clearances

- Clearances to poles
 - Minimum lateral passing clearance between tram vehicle and pole is 675 mm.
 - Minimum vertical passing clearance between tram vehicle and pole is 250 mm.
- Clearance to persons
 - Minimum vertical clearance between public or restricted access standing surfaces and live parts of the OLE is 5200 mm.
- Electrical and mechanical clearances
 - Minimum static electrical clearance between live parts of the OLE, including any non-insulated 750 V conductor and earth or any metal at earth potential is 100 mm.
 - Minimum passing electrical clearance between live parts of the OLE, including pantograph, and structures or earth is 50 mm. Allowance is made for contact wire uplift, pantograph sway, track tolerances and wear of the pantograph and contact wire.
 - Minimum mechanical clearance between pantograph and live metal is 80 mm, except to steady arms attached to the contact wire, where it is 15 mm. These clearances allow for contact wire uplift, pantograph sway, track tolerances and wear of the pantograph and contact wire.

2.2.7. Earthing and Bonding

Accessible voltages should not exceed 60 V (CENE11) and the design of electric traction power supply should ensure it.

- Poles
 - Poles are not bonded directly to running rails as this would create an undesirable path for stray DC current to return to the substation, i.e. via the ground and any buried services. Poles are protected from fault currents by double insulation between it and the contact wire.
- Cross bonding
 - To reduce stray currents to an acceptable level, the traction return rails are cross bonded at regular intervals to provide a parallel low resistance path for return currents to the substation.



- Structures at Risk to Fault Currents

Confirmation is sought as to whether this arrangement was installed:

- Where poles may be at risk to fault currents resulting in unacceptable touch voltages, e.g. a feeder pole that carries traction feeder cables, a voltage limiting device is connected between the pole and the running rails.
- Metallic structures inside the contact wire de-wirement zone are not bonded directly to running rails but instead are connected to them using a VLD, to mitigate against dangerous touch voltages.

2.3 DESIGN SPECIFICATIONS

In this section the main geometrical, electrical and mechanical design parameters are provided. These parameters will be used as the basis for OLE design. Parameters are obtained from previously issued documentation, applicable standards and usual design considerations.

2.3.1. Overhead Line Equipment Performance Specification

2.3.1.1. Electrical ratings

The nominal working supply voltage will be 750 V DC. The maximum voltage (short time transient voltage) will be 3500 V DC.

The long-term operational load, considering a maximum permanent temperature of 80 °C in the wire, a wind speed of 1 m/s and a standard solar radiation of 900 W/m², will be 667 A. This value has been calculated for a single copper contact wire with a cross section area of 150 mm², whose characteristics have been taken from international standards. Detailed calculations will be shown in Section 3.1.

2.3.1.2. Contact wire

The contact wire will be a fixed termination trolley wire (single hard drawn copper contact wire) with a cross section area of 150 mm².



2.3.1.3. Wire heights

The minimum wire height will be 5200 mm, the nominal wire height will be 5800 mm and the maximum wire height will be 6300 mm.

2.3.1.4. Maximum span length

The street-running maximum span length is obtained based on wire design height of 6000 mm, a contact wire tension of 15 kN at -15°C and 1.334 kg/m of mass per unit length of the contact wire.

According to the *Office of Rail Regulation (ORR) - Guidance on Tramways (OFFI06)*, the contact wire or any other live part of the overhead electric traction supply system always has to be over 5.200 m above the highway, even when one support fails.

Under this condition and input data, the maximum span length of 25 m has been determined. Detailed calculations will be shown in Section 3.2.1.

2.3.1.5. Wire gradients and staggers

The maximum wire gradient and the maximum change of gradient are extracted from EN 50119 (CENE09). In the table below (*Table 2.1*), the limitation of the speed in relation to the gradient of the contact wire is shown. Interpolation shall be allowed where there is no direct comparable speed.

Table 2.1. Wire gradients (extracted from EN 50119)

Speed up to km/h	Maximum gradient		Maximum change of gradient	
		‰		‰
50	1/40	25	1/40	25
60	1/50	20	1/100	10
100	1/167	6	1/333	3

The nominal contact wire stagger will be ± 200 mm and the maximum mid-span offset, 380 mm.

Should these values be exceeded, it will be properly justified in the design report.

2.3.1.6. Uplift

The typical nominal uplift of the contact wire at the support is expected to be 25 mm, but will depend on the contact force provided by the single pantograph configuration.



2.3.1.7. Environmental Requirements

The outdoor environment specific to *Birmingham* and *Wolverhampton* is defined in the table below. Ambient temperatures have been taken from the contract definitions and the wind speeds from accepted published data using methods specified in the International Standards. Very severe icing of the overhead line will be allowed, again as required by International Standards.

Table 2.2. Environmental Requirements

Maximum design temperature	35 °C
Minimum design temperature	-15 °C
Rainfall average annual	800 mm
Maximum design wind speed	25 m/s
Maximum survival gust speed in exposed conditions	42 m/s
Maximum ice loading radial thickness at 25 m/s wind	10 mm

The extreme mean-hourly wind speed likely to be exceeded only once in 50 years is 25 m/s (operational case). This is also to include 10 mm ice loading on the structure, cables and other surfaces, but not on the contact wire.

Additionally, there are two survival cases:

- The operational case, but including 10 mm radial ice on the contact wire.
- The case of having no ice on any structure, but a gust speed of 42 m/s.

2.3.1.8. Electrical and Mechanical Clearances

The minimum static electrical clearance between any non-insulated 750 V DC conductors or other live parts of OLE and earth or structures at earth potential will be 75 mm.

The minimum passing clearance between live parts, including the pantograph and fixed earth installations, will be 25 mm.

The minimum mechanical clearance between pantograph and common live metal will be 75 mm except to registration arms attached to the contact wire where it will not be less than 15 mm.

These clearances are obtained after due allowance has been made for dynamic movement and the effect of track tolerances and wear of the pantograph and contact wire.

Clearances between separate OLE equipment should be at least 80 mm.

All these clearances exceed the minimum figures quoted in the standards.



2.3.1.9. Visual Appearance

In order to make the overhead line as acceptable as possible in terms of visual appearance, small diameter wire and discreet insulators will be used and the clutter will be limited.

2.3.2. Structural and Mechanical Calculations

2.3.2.1. Static weights of equipment

Static stress in the supporting structure is created due to the equipment's and structures' self-weight.

2.3.2.2. Radial component of wire tension

The contact wires contribute to the radial forces onto supports due to curvature of the track and/or stagger.

2.3.2.3. Ice layer

A layer of ice is to appear under severe weather conditions in all supporting wires and steelwork. This ice contributes extra mass and extra wind resistance. The maximum ice loading radial thickness will be 10 mm.

2.3.2.4. Wind loading on the supports

The design wind speed is considered to be at a right angle to the track centreline.

Wind speeds are defined by the local historical weather records. These will define the speeds and frequencies for extreme conditions. There are two values for the wind loading on OLE and structures:

- A maximum operation wind speed of 25 m/s (the speed at which normal tram service would continue).
- A maximum survival gust speed of 42 m/s (the speed at which the system would survive without damage).

2.3.2.5. Safety factors

Safety factors on new equipment will be 1,3, to be compliant with EN 50119 (CENE09).



2.3.3. Electro-Magnetic Compatibility (EMC)

EMC management of the *WCCE* project is extremely important both for the safe operation of the tramway on completion and the impact of the project on non-tramway systems, outside the boundary of the *WCCE*.

In order to ensure that the *WCCE* project meets both the contractual and statutory obligations inherent its design of the tramway systems installation, the proposed infrastructure must be monitored and controlled in a planned manner. In particular EMC must be achieved for the system by the use of a suitable management strategy.

Although OLE design once wires are chosen is a mostly mechanical design, the interface with the pantograph, however, can generate Electro-Magnetic Interferences (EMI), which can be radiated by the overhead wire system and to the surroundings. The extent of emissions depends heavily on the design of the pantograph and its ability to follow the overhead wire. EMI are not generated by the OLE equipment itself, however the interface between the tram pantograph and the contact wire is not perfect and small arcs are produced as the tram moves under normal operation. These arcs and transients are EMI that can affect other nearby electrical/electronic systems.

Both traction systems (trackside and on board) can generate harmonics for different frequencies and these can be transmitted by the OLE system.

However, the study of EMC and EMI exceeds the limits of this Master's Project.

2.4 DESIGN DECISIONS

2.4.1. OLE Design Parameters

The following parameters have been assumed in order to develop the OLE layout design:

- Single contact wire of 150 mm² section.
- Variable tension (fixed termination) contact wire with only one continuous tension length.
- Contact wire height
 - Normal minimum 5200 mm.
 - Nominal 5800 mm.
 - Normal maximum 6300 mm.



- Contact wire stagger
 - 200 mm tangent track – nominal.
 - 380 mm curved track – maximum mid-span offset.
- Maximum span length street-running 25 m.
- Where two contact wires converge, termination of contact wire at junctions will be as per existing arrangement at *Bilston Street*, i.e. one contact wire is terminated onto the other contact wire via a clamp assembly.

2.4.2. Support Poles

It is anticipated that stepped circular hollow sections will be preferred where poles are required, to match the existing poles in the *Bilston Street* area. Consequently, poles will be steel tube galvanised inside and out. According to its application, the pole diameter will vary, but it is likely to be an average of 250 mm. To attach poles to the foundation, bolt cluster and flange plate will be used, which will be buried below ground in the street areas to provide a smooth surface around the pole. The contact wire height and the offset of the pole from the track determine the height of the pole, but it is likely to be an average of 8 m to 9 m above rail level.

The preferred type of pole is the combined pole for OLE and street lighting. For the *WCCE* layout, these have been considered where a street lighting pole already exists and is a suitable location for the OLE support.

All OLE poles that are liable to high vehicle traffic areas will require protection. Once detailed design is underway, consideration must be given to those areas.

2.4.3. Foundations

Reinforced concrete is the typical foundation construction. The type of ground and proximity of buried services condition the type of foundation to be used. It is anticipated that foundations will be hand excavated or mechanically grabbed, since *WCCE* is a street area with a high density of buried services. The choice of foundation would be side bearing where the ground is suitable, because the foundation resists the overturning force of the pole created by the OLE by relying on the ground. Therefore, the depth of this type of foundation is typically 2 m to 4 m. When the foundation is hand excavated, the plan size depends on the size of the hole for safe excavation and when it is mechanically grabbed, this plan size depends on the size of grab bucket. The plan size varies typically from 0.6 m x 0.6 m to 1.2 m x 1.0 m.



A gravity slab type foundation can be used where the ground has poor overturning resistance or where the foundation depth is restricted. To resist the overturning force, this type of foundation relies on the mass of the slab. This type of foundation is shallow (0.6 m to 1.0 m deep) but a large plan size (4.5 m x 2.0 m).

2.4.4. Building Fixings

The preferred type of OLE support is the use of building fixings, since the amount of street furniture is minimised and the visual impact of the OLE is reduced. The along-track position, the height and the suitability to withstand the applied load determine the suitability of the building for fixing to.

Typical fixings are between 6 m and 8 m above rail level, depending on the offset of the building from the track and the applied load. The anticipated horizontal load can be varied between 1 kN and 10 kN by varying the height of the fixing, but its value is typically 5 kN. The horizontal load will be decreased by an increase in height of the fixing. To achieve adequate clearance where a cross-span wire of a backbone arrangement crosses over the near contact wire to reach the far contact wire, in a double track area, further increase in fixing height may be necessary.

Further investigation will be required to determine the suitability of the building fixing to withstand the applied load. If any building proves unsuitable then the OLE layout should be amended to a suitable location for a fixing, where possible. If an alternative location is not possible, a pole will be required.

The typical arrangement of a single fixing into a traditional stone or masonry building uses a M20 screw anchor with an eye fitting for attaching the span wire. A plate anchored to the building can be used for fixing multiple span wires.

More modern structures, such as the new steel and glass clad Bus Station, and the proposed Block 10 and Rail Station developments, are likely to require a bespoke more complex fixing arrangement which should be accommodated within the design of the structure, where practical.



2.5 *OLE LAYOUT DEVELOPMENT*

2.5.1. Design Development

The route has been divided into five sections in developing the design, reflecting varying track geometrics, fronting property and engineering, aesthetic and physical requirements. A descriptive overview of the principle support system proposed for each of the sections defined is provided.

2.5.2. Junction of Bilston Street and Piper's Row

Significant amendments and additions to the OLE support system will be required, in order to accommodate the divergence and merge of WCCE from the existing Metro infrastructure.

A careful consideration of how best to integrate and rationalise the existing with new supporting infrastructure will be required due to the complexities of the area. Beyond the requirements of ensuring a specification compliant contact wire, the following should be considered in undertaking detailed design:

- Ground conditions.
- Accommodation and protection of poles within footways and islands.
- Building fixing compatibility (if appropriate).
- Suitability of existing support infrastructure to accommodate additional pull off loads, etc.
- Rationalisation of existing and new support structures (overview check).

Two existing OLE poles are used to place cantilever arms belonging to WCCE. It was decided to use a side-bridle arrangement structure with pull-off arrangement (or backbone arrangement) due to the following reasons:

- The small track radii, which originates sufficiently high values of the radial load to allow steady arms to be supported from only one side of the track, instead of being supported by cross-span wires, as usual.
- The desire to use as few poles within footways and islands as possible, to reduce the risk of being hit by traffic and also to avoid the necessity of protecting the poles from vehicles (as it was mentioned before).



2.5.3. Piper's Row: Bus Station to Berry Street

As there is both a horizontal and vertical curvature to the track in the new line running into the *Piper's Row* area, building support and poles will be required. To ensure correct registration of contact wire, the utilisation of poles may be necessary at some locations.

A number of buildings and structures within *Piper's Row* may be suitable for fixing OLE support wires to, according to some investigations. This includes *Wolverhampton Bus Station*, *CRC Manhattans*, *Wulfrun Hotel*, *The Co-operative*, *The Britannia Hotel* and the proposed *Block 10* development. All building fixings will need to be assessed to ascertain that the tension loading for the support systems does not exceed the maximum pull out force.

In the junction of *Tower Street* and *Piper's Row*, it was decided to use a side-bridle arrangement structure, to avoid placing a pole in the middle of the crossing where other vehicles circulate. A new OLE pole is located near the electrical substation, pole no. 10, to avoid using a fixing to the substation building. It should be stressed that this pole, apart from the side-bridle arrangement structure, supports a cantilever arm to register the contact wire of the nearest track to the substation.

Regarding pole no. 14 and building fixings no. 3, 4 & 5, it is important to note that a side-bridle arrangement structure is used again. This is due to the differences between the radii of both tracks in that section, what makes hardly viable to use a cross-span wire. Additionally, there is no possibility to place a pole in the junction of the streets because of the traffic, what supports the decision of using a side-bridle arrangement structure.

Building fixing no. 8 supports a cross-span wire, whose other end is located at existing street lighting pole. The decision of using existing street lighting poles no. 16 & 17 has been made to avoid installing fixings at the *Queen's Building* and in the case of existing street lighting pole no. 18, given the remoteness to buildings in that section.



2.5.4. Junction of Lichfield Street, Victoria Square and Railway Drive

The main feature of the area going north on *Piper's Row* towards the junction with *Railway Drive* is arrangement of the track radii through the highway junction coupled with the rise in carriageway levels towards the *Railway Drive* overbridge.

The facility is considered particularly important in the junction, given the narrowness of parts of the footway fronting *Railway Drive* and because there is little opportunity to fix supporting wires to buildings to the outside of the track curve.

Once the decision of placing poles no. 19 & 20 in the external corners of the junction is made, it was decided to use them together with building fixing no. 13 and pole no. 21 to install a side-bridle arrangement structure with pull-off arrangement (or backbone arrangement). Again, this is possible due to the small track radii. The following difficulties are surmounted by adopting the mentioned solution:

- Remoteness of the west façade of *Block 10* to the track.
- Specific characteristics of *Block 10*, which allows installing building fixings only in the master pillars of the block.

Cross-span wires are used within the north façade of *Block 10* because of the appropriate position of the master pillars in this façade. The other ends of the cross-spans are located at new OLE poles.

2.5.5. Railway Drive Overbridge

Some of the more difficult challenges for the design of the OLE are provided by the *Ring Road* overbridge, along *Railway Drive*, in so far as its vertical profile and construction requires more careful consideration and analysis.

To ensure the contact wire maintains clearance to the carriageway, a greater level of support is required. A further consideration is the desire to maintain access to the '*Banana Yard*' development located on the north side of the *Birmingham Canal*.

Within and over the bridge, considerations have been given to where and how fixings and pole installations could be located. In order to remove the need for support poles in the centre of the bridge, the use of a catenary system spanning from one side of the bridge to the other has been examined. However, this system would require significantly larger poles either side the bridge and a far more complex web of support wires between.



Many other options have been examined. Though, the preferred solution is the use of central poles fixed to the outside of the central bridge support pier or founded in the ground at the lower carriageway level, rising above the bridge deck. There are many advantages to implementing this solution, including that the support network is less complex than a catenary and that the bridge deck is kept clear of equipment.

Going forward, the major issues that will need to be considered in greater detail are the following:

- Weight constraints of the bridge.
- Fixing positions and tension requirements to the outside façade of the bridge parapets.
- Ground conditions in the vicinity of bridge pillar.
- Camber and drop of the existing surface of the bridge.
- Height of vehicle requirements over the bridge.
- Construction and maintenance requirements.

2.5.6. Wolverhampton Railway Station Area

The use of poles is more likely because there is a combined run of two slight curves, including a change in vertical alignment, in the approach to the proposed *Railway Station* area and into the Tram Stop, which constrains the use of building fixings. Thus, OLE poles are used around the curve, the *Railway Station* and in front of the proposed hotel development.

Again, the will to maintain access to the '*Banana Yard*' development located on the north side of the *Birmingham Canal* has been taken into account, conditioning the position of poles no. 31 to 44. In this section, cross-span wires or cantilever arms supported by poles are used.

After the turnout, approaching the *Rail Station*, there is only one track. In this section, poles with cantilever arms located at one side of the track are used.



Chapter 3 CALCULATIONS

3.1 ELECTRICAL CALCULATIONS

3.1.1. Long-term operational load

The current-carrying capacity of a conductor (I) can be obtained from (KIES09):

$$I = \sqrt{(N_C + N_R - N_S)/R'_T}$$

where

- N_C is the energy loss by convection in W/m,
- N_R is the energy loss by radiation in W/m,
- N_S is the solar radiation in W/m and
- R'_T is the resistance at temperature T in Ω/m .

The energy loss by convection can be calculated from:

$$N_C = \pi \cdot \lambda \cdot Nu \cdot (T - T_{amb})$$

where

- λ is the thermal conductivity of air in W/K·m,
- $T = 80$ °C is the temperature of the conductor (Cu, in operating conditions) (CENE09),
- $T_{amb} = 35$ °C is the ambient temperature and
- Nu is the Nuβelt number, which depends on the Reynolds number (Re):

$$Nu = 0,65 \cdot Re^{0,2} + 0,23 \cdot Re^{0,61}$$

The Reynolds number is given by:

$$Re = V \cdot D \cdot \gamma/\eta$$

where

- $V = 1$ m/s is the wind velocity (CENE09),
- $D = 0,014$ m is the conductor diameter,
- γ is the specific mass of air in kg/m³ and
- η is the dynamic viscosity in N·s/m².



For practical calculations, the characteristics of air should be evaluated for the mean value:

$$T = \frac{T + T_{amb}}{2} = \frac{35 \text{ }^{\circ}\text{C} + 80 \text{ }^{\circ}\text{C}}{2} = 57,5 \text{ }^{\circ}\text{C}$$

Interpolating:

- $\gamma = 1,0675 \text{ kg/m}^3$
- $\lambda = 0,0285 \text{ W/K}\cdot\text{m}$
- $\eta = 0,202 \cdot 10^{-4} \text{ N}\cdot\text{s/m}^2$

The energy loss by radiation is given by:

$$N_R = k_s \cdot k_e \cdot D \cdot \pi \cdot (\theta^4 - \theta_{amb}^4)$$

where

- k_s is the Stefan-Boltzmann constant equal to $5,67 \cdot 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$,
- $k_e = 0,75$ is the emission coefficient (Cu, heavily oxidized) (KIES09),
- $\theta = 353 \text{ K}$ is the absolute temperature of the conductor and
- $\theta_{amb} = 308 \text{ K}$ is the absolute ambient temperature.

The solar radiation is taken from:

$$N_S = k_a \cdot D \cdot N_{Sh}$$

where

- $k_a = 0,75$ is the absorption coefficient (Cu, heavily oxidized) (KIES09) and
- $N_{Sh} = 900 \text{ W/m}^2$ is the standard solar radiation.

The resistance R'_T is different for AC and DC currents due to skin, spiral and magnetic effects. However, for the dimensions and composition of conductors used for contact lines, the DC resistance may also be adopted for AC applications. Therefore, the resistance at temperature T is:

$$R'_T = R'_{20} \cdot [1 + \alpha_R \cdot (T - 20)]$$

where

- R'_{20} is the DC resistance at $20 \text{ }^{\circ}\text{C}$ in Ω/m and
- $\alpha_R = 3,8 \cdot 10^{-3} \text{ K}^{-1}$ is the thermal coefficient of resistance (CENE12a).



The resistance per unit length of wires and conductors is calculated by:

$$R'_c = \rho/S$$

where

- $\rho = 0,01777 \Omega \cdot \text{mm}^2/\text{m}$ is the specific resistivity of the conductor at 20 °C (CENE12a) and
- $S = 150 \text{ mm}^2$ is the cross section.

Then, the current-carrying capacity will be $I = 667 \text{ A}$.

3.1.2. Short-circuit current

The short-circuit capacity of a conductor (I_{th}) can be calculated from (KIES09):

$$I_{th} = S \cdot \sqrt{\frac{c \cdot \gamma}{\rho \cdot \alpha_R \cdot t_k} \cdot \ln \left(\frac{1 + \alpha_R \cdot (T_{lim} - 20)}{1 + \alpha_R \cdot (T_1 - 20)} \right)}$$

where

- $S = 150 \text{ mm}^2$ is the cross section,
- $c = 390 \text{ J/kg} \cdot \text{K}$ is the specific heat (CENE12b),
- $\gamma = 8900 \text{ kg/m}^3$ is the specific mass of Cu (CENE12b),
- $\rho = 1,777 \cdot 10^{-8} \Omega \cdot \text{m}$ is the specific resistivity of the conductor at 20 °C (CENE12a),
- $\alpha_R = 3,8 \cdot 10^{-3} \text{ K}^{-1}$ is the thermal coefficient of resistance (CENE12a),
- $t_k = 1 \text{ s}$ is the duration of the short-circuit current (CENE09),
- $T_{lim} = 170 \text{ °C}$ is the permissible maximum temperature of the conductor (Cu) in case of a short-circuit (CENE09) and
- $T_1 = 80 \text{ °C}$ is the initial temperature of the conductor (Cu) when the short circuit occurs (CENE09).

Then, the short-circuit current will be $I_{th} = 16856,82 \text{ A}$.



3.2 MECHANICAL CALCULATIONS

3.2.1. Maximum span length

Conductor displacement caused by wind is the decisive overhead contact line factor governing longitudinal span lengths.

For straight track, the maximum possible longitudinal span length (l_{max}) is determined using the following equation:

$$l_{max} = \sqrt{\frac{2 \cdot H}{F'_W} \cdot \left(2 \cdot e_{per} - b_1 + b_2 + \sqrt{(2 \cdot e_{per} - b_1 + b_2)^2 - (b_1 + b_2)^2} \right)}$$

Where H is the horizontal component of the tensile force acting along the conductor, F'_W is the wind load per unit length, e_{per} is the contact wire lateral position permitted and b_1 and b_2 are the lateral positions of the contact wire at supports.

The maximum possible longitudinal span length in a curve depends on whether the wind blows from inside the curve or from outside the curve. For practical applications, only the case where the wind blows from outside the curve is of significance. The equation for the maximum possible longitudinal span length in a curve when the wind blows from outside the curve is:

$$l_{max} = \sqrt{\frac{2 \cdot H}{F'_W + H/R} \cdot \left(2 \cdot e_{per} + b_1 + b_2 + \sqrt{(2 \cdot e_{per} + b_1 + b_2)^2 - (b_1 - b_2)^2} \right)}$$

Where R is the radius of the curve.

The permissible contact wire position (e_{per}) depends on the maximum lateral contact wire position (e_{max}) and the sway of the pantograph (r).

$$e_{per} \geq e_{max} - r$$

The maximum lateral position (e_{max}) is obtained from

$$e_{max} = e_{1,2} + \Delta b_{max} + t_s + t_p$$

Where $e_{1,2}$ is the contact wire lateral displacement due to stagger and wind deflection, Δb_{max} is the maximum lateral contact wire displacement due to temperature, t_s is the tolerance of stagger and t_p is the deflection of pole due to wind (KIES09).



Some values for the maximum span lengths in relation with the radius of the curves are given:

Table 3.1. Maximum span lengths in relation with the radius of the curves

Radius (m)	Maximum span length (m)
25	9,8
30	10,6
35	11,45
40	12,16
50	13,42
80	16,47
100	18,11
300	25
500	25
2500	25

3.2.2. Loads

Loads can be classified as permanent and variable actions, in accordance with civil engineering principles. Dead weights and permanently acting tensile forces can be grouped under the first category and under the second, wind and ice loads (KIES09).

3.2.2.1. Permanent actions on conductors

3.2.2.1.1. Self-weight

The load per unit length of a contact wire (G'_{CW}) is calculated using the following equation (KIES09):

$$G'_{CW} = m'_{CW} \cdot g$$

where

- $m'_{CW} = 1,334$ kg/m is the mass per unit length of the contact wire and
- $g = 9,81$ m/s² is the acceleration because of gravity.

Therefore, the load per unit length of the contact wire will be $G'_{CW} = 13,1$ N/m.

For a 22 m span length, the self-weight of the contact wire will be $G_{CW} = 288,2$ N.

3.2.2.1.2. Radial forces

Radial forces occur in contact wires because of the change of direction of the overhead line at supports. Its value should remain within a specified range. It can be augmented by increasing the contact wire stagger at the support or reducing the span length.



The radial force must be checked in conjunction with the wind load, because its value can exceed the permissible one if the wind force acts in the same direction as the radial force. Furthermore, the determination of radial forces affects the examination of pole torsion (KIES09).

The radial force in a straight section can be calculated using the following equation (GARC14):

$$R_Y = N \cdot T_{CW} \cdot \left[\frac{D - D_0}{L_{V0}} + \frac{D - D_1}{L_{V1}} \right]$$

where

- $N = 1$ is the number of contact wires,
- $T_{CW} = 15$ kN is the tensile force acting on the contact wire,
- D_0 , D and D_1 are the lateral positions of the contact wire at the supports in m and
- L_{V0} and L_{V1} are the span lengths in m.

Note: “0” refers to the span which is before the one where the radial force is being calculated and “1” refers to the next span.

The radial force in a curved section can be obtained from (KIES09):

$$R_Y = N \cdot T_{CW} \cdot \left[\frac{D_0 - D}{L_{V0}} + \frac{D_1 - D}{L_{V1}} \pm \frac{L_{V0} + L_{V1}}{2 \cdot R} \right]$$

where

- R is the curve radius in m.

The last term of the equation is positive if pulling from the pole to the track (pull-off support) and negative if pushing to the pole (push-off support).

If $D = 0,2$ m, $D_0 = D_1 = -0,2$ m and $L_{V0} = L_{V1} = 22$ m, the radial force in the straight section will be $R_Y = 545,45$ N.

If $D = 0,2$ m, $D_0 = D_1 = -0,2$ m, $L_{V0} = L_{V1} = 9$ m and $R = 25$ m, the radial force in the curved section when pulling from the pole to the track will be $R_Y = 4854,55$ N.

3.2.2.2. Variable actions on conductors

3.2.2.2.1. Wind load

The wind load per unit length acting perpendicularly on a conductor or wire (F'_w) can be obtained from (CENE09):

$$F'_w = q_z \cdot G_C \cdot C_C \cdot d$$

where



- $G_C = 0,75$ is the structural response factor for conductors taking into account the response of movable conductors to wind loads,
- $C_C = 1,0$ is the drag factor of the conductor,
- $d = 0,014$ m is the diameter of the conductor and
- q_z is the characteristic dynamic wind pressure in N/m^2 according to

$$q_z = \rho/2 \cdot G_q \cdot G_t \cdot V^2$$

where

- $\rho = 1,225$ kg/m^3 is the air density,
- $G_q = 2,05$ is the gust response factor,
- $G_t = 1,0$ is the terrain factor taking into account the protection of lines, e.g. in cuts, cities or forests and
- $V = 42$ m/s is the survival gust speed in m/s.

Therefore, the wind load per unit length in exposed conditions will be $F'_W = 23,26$ N/m.

For a 22 m span length, the wind load on the contact wire will be $F_W = 511,72$ N.

3.2.2.2.2. Ice load

Snow and ice load shall be taken into account at temperatures up to + 5 °C, where applicable. The load should be specified as nominated in *Table 3.2*, which contains values that are valid for conductors in the usual diameters, i.e. 10 mm and 20 mm (CENE10).

Table 3.2. Ice loads

Class	Ice load N/m
I0 (no ice)	0
I1 (low)	3,5
I2 (medium)	7
I3 (heavy)	15

Due to the environmental conditions, a medium load (I2) has been taken into account. Then, the ice load per unit length on the contact wire will be $F'_I = 7$ N/m and the ice load on a 22 m span length, $F_I = 154$ N/m.



3.2.2.3. Permanent actions on poles

3.2.2.3.1. Self-weight

The load per unit length of a pole (G'_p) is calculated as before:

$$G'_p = m'_p \cdot g$$

where

- $m'_p = 30$ kg/m is the mass per unit length of the pole (assuming an average diameter of 250 mm) and
- $g = 9,81$ m/s² is the acceleration because of gravity.

Therefore, the load per unit length of the pole will be $G'_p = 294,3$ N/m.

For a 8 m height of the pole, its self-weight will be $G_p = 2354,4$ N.

On the other hand, a cantilever load of 500 N is assumed.

3.2.2.3.2. Horizontal forces

Horizontal forces acting on poles are due to the radial forces of head-span and cross-span wires.

The value of these forces should be evaluated for each case (KIES09).

3.2.2.4. Variable actions on poles

3.2.2.4.1. Wind load

According to EN 50119 (CENE09), wind forces on structures can be calculated with the following equation:

$$Q_{Wstr} = q_z \cdot G_{str} \cdot C_{str} \cdot A_{str}$$

where

- q_z is the dynamic wind pressure in N/m² (as calculated in Section 0),
- $G_{str} = 1$ is the structural resonance factor for self-supporting steel and concrete structures typically used for overhead contact lines,
- $C_c = 0,7$ is the drag factor depending on the shape and surface roughness of the structure, in this case, tubular steel and concrete structure with circular cross section and
- A_{str} is the projected area of the structure, equal to

$$A_{str} = h \cdot d$$

where

- $h = 8$ m is the height of the pole and
- $d = 0,25$ m is the diameter of the pole.

Therefore, $Q_{Wstr} = 3100,9$ N.

3.2.2.4.2. Ice load

It is required to consider a 10 % increase in weight of both the pole and the cantilever due to ice loads. Therefore, the weight of a pole with ice will be $G_P = 2589,84$ N and the weight of a cantilever with ice, 550 N.

3.2.3. Geometry of the cross-span arrangements

Once the loads acting on conductors are known, the geometry can be calculated. The calculation method varies if the contact wire is supported by poles with cantilevers or by cross-spans.

For this project, the geometry does not have to be studied for poles with cantilevers, because there is a catalogue with the cantilevers that can be used. This means that they do not have to be designed. It only has to be proved that they can withstand the loads.

However, the geometry is different for each cross-span support and is important in order to design the arrangements. A summary of the method used for this task is given below (KIES09). It is important to notice that no safety factors have been considered for the calculation of the geometry.

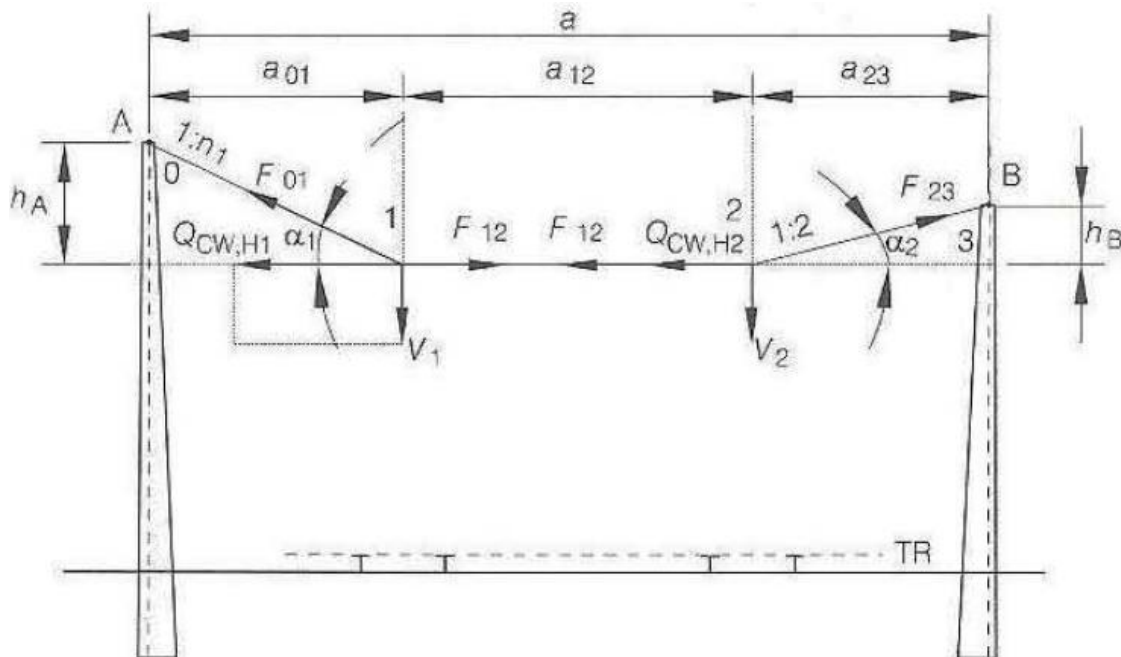


Figure 3.1. Geometry of the cross-span arrangement



A cross-span for a double-track line is shown in Figure 3.1. The loads V_1 and V_2 follow from the contact wires, as well as the radial forces $Q_{CW,H1}$ and $Q_{CW,H2}$. Since the radial forces act in the direction of pole A, the wire 0-1 is designed to carry the load V_1 . The gradient of the wire can be chosen between 1:10 and 1:15. The following applies to the tensile force of the wire 0-1:

$$F_{01} = V_1 / \sin \alpha_1 \sim V_1 / \tan \alpha_1 = V_1 \cdot a_{01} / h_A$$

The transverse wire in between the supports carries the load

$$F_{12} = Q_{CW,H1} + F_{01} \cdot \cos \alpha_1 \approx Q_{CW,H1} + V_1 \cdot a_{01} / h_A$$

The wire 2-3 supporting support 2 carries the resultant force from F_{12} , $Q_{CW,H2}$ and V_2 and has to be arranged in the direction of their action. Since the gradient of the tensile wires is low only, it applies

$$F_{23} \sim F_{12} + Q_{CW,H2} = Q_{CW,H1} + Q_{CW,H2} + V_1 \cdot a_{01} / h_A$$

The gradient of the wire 2-3 follows from

$$\tan \alpha_2 = V_2 / (Q_{CW,H1} + Q_{CW,H2} + V_1 \cdot a_{01} / h_A)$$

For the distance a_{23} to the pole the difference between the height of support 2 and the attachment at the pole follows:

$$h_B = a_{23} \cdot \tan \alpha_2$$

The poles A and B will be rated for the forces F_{01} and F_{23} respectively, which act at a height corresponding to the sum of contact wire height, the design height of the supports and the values h_A and h_B , respectively.

If $V_1 = 190,6 \text{ N}$; $V_2 = 190,1 \text{ N}$; $Q_{CW,H1} = 422,6 \text{ N}$; $Q_{CW,H2} = 419,6 \text{ N}$; $a_{01} = 6,26 \text{ m}$ and $a_{23} = 7,62 \text{ m}$, then

$$h_A = \frac{6,26}{15} = 0,4173 \text{ m}$$

$$F_{01} = 190,6 \cdot \frac{6,26}{0,4173} = 2859 \text{ N}$$

$$F_{12} = 422,6 + 2859 = 3281,6 \text{ N}$$

$$F_{23} = 3281,6 + 419,6 = 3701,2 \text{ N}$$

$$h_B = 7,62 \cdot \frac{190,1}{3701,2} = 0,3914 \text{ m}$$



3.2.4. Calculation of the reaction forces in the supports of cross-spans

The reaction forces in the supports shall be calculated for each of the cases mentioned in EN 50119 (CENE09), i.e.

- **Case A:** Permanent loads, conductor tensile forces at the minimum and design temperature shall be considered.
- **Case B:** Permanent loads, conductor tensile forces increased by the action of wind and wind loads on each element acting in the most unfavourable direction shall be considered.
- **Case C:** Permanent loads, conductor forces increased by the ice loads and ice loads on structures shall be considered.

For this calculation, safety factors have been considered. It is stated in EN 50119 (CENE09) that a safety factor of 1,3 shall be considered for permanent and variable (wind and ice) actions.

To calculate the reaction forces, the balance point shall be calculated for each case. Thus, the following equations have been used in each node (UNIV06):

$$\sum F_X = 0$$

$$\sum F_Y = 0$$

Additionally, the conservation of lengths has been used:

$$L_X = a_{01} + a_{12} + a_{23} = L_{01} \cdot \cos \alpha_1 + L_{12} \cdot \cos \alpha_3 + L_{23} \cdot \cos \alpha_2$$

$$L_Y = h_A + h_B = L_{01} \cdot \sin \alpha_1 + L_{12} \cdot \sin \alpha_3 + L_{23} \cdot \sin \alpha_2$$

Where H_A , H_B , V_A and V_B are the horizontal and vertical forces at the supports (as shown in Figure 3.2), α_3 is the angle between L_{12} and the x axle and the rest of the parameters are taken from Figure 3.1. Geometry of the cross-span arrangement

Case A

If $V_1 = 190,6 N$; $V_2 = 190,1 N$; $Q_{CW,H1} = 422,6 N$; $Q_{CW,H2} = 419,6 N$; $a_{01} = 6,26 m$; $a_{12} = 4,41 m$ and $a_{23} = 7,62 m$, then $H_A = 3716,8 N$; $H_B = 4811,6 N$; $V_A = 247,8 N$ and $V_B = 247,1 N$.

Case B (wind from the left)

If $V_1 = 190,6 N$; $V_2 = 190,1 N$; $Q_{CW,H1} = 422,6 N$; $Q_{CW,H2} = 419,6 N$; $F_{W,H1} = 350,8 N$; $F_{W,H2} = 349,9 N$; $a_{01} = 6,26 m$; $a_{12} = 4,41 m$ and $a_{23} = 7,62 m$, then $H_A = 3353,5 N$; $H_B = 5359,3 N$; $V_A = 228 N$ and $V_B = 267 N$.



Case B (wind from the right)

If $V_1 = 190,6 N$; $V_2 = 190,1 N$; $Q_{CW,H1} = 422,6 N$; $Q_{CW,H2} = 419,6 N$; $F_{W,H1} = 350,8 N$; $F_{W,H2} = 349,9 N$; $a_{01} = 6,26 m$; $a_{12} = 4,41 m$ and $a_{23} = 7,62 m$, then $H_A = 4113,2 N$; $H_B = 4297,2 N$; $V_A = 267,8 N$ and $V_B = 227,1 N$.

Case C

If $V_1 = 190,6 N$; $V_2 = 190,1 N$; $Q_{CW,H1} = 422,6 N$; $Q_{CW,H2} = 419,6 N$; $F_{I,H1} = 101,9 N$; $F_{I,H2} = 101,7 N$; $a_{01} = 6,26 m$; $a_{12} = 4,41 m$ and $a_{23} = 7,62 m$, then $H_A = 5954 N$; $H_B = 7048,8 N$; $V_A = 393,2 N$ and $V_B = 366,5 N$.

3.2.5. Foundations

In line with EN 50119 (CENE09), foundation of supports shall be capable of transferring the structural loads resulting from the actions on the support into the subsoil. For this reason, when designing foundations the following items should be taken into account:

- design loads and design formulae,
- configuration of the foundation,
- limiting values of displacements,
- geotechnical design parameters taking into account groundwater levels,
- design parameters for structural materials,
- support/foundation interconnections,
- foundation construction and installation,
- special loads,
- electrical resistance of the foundation to earth.

Once the loads acting on the poles are known, the moment on the base shall be calculated. A safety factor of 1,3 shall be considered. A summary of the method used for this task is given below.

Special attention should be paid to the distances between the point where the force is applied and the point where the moment is being calculated, because they are different for each pole, as it was mentioned in Section 3.2.3.

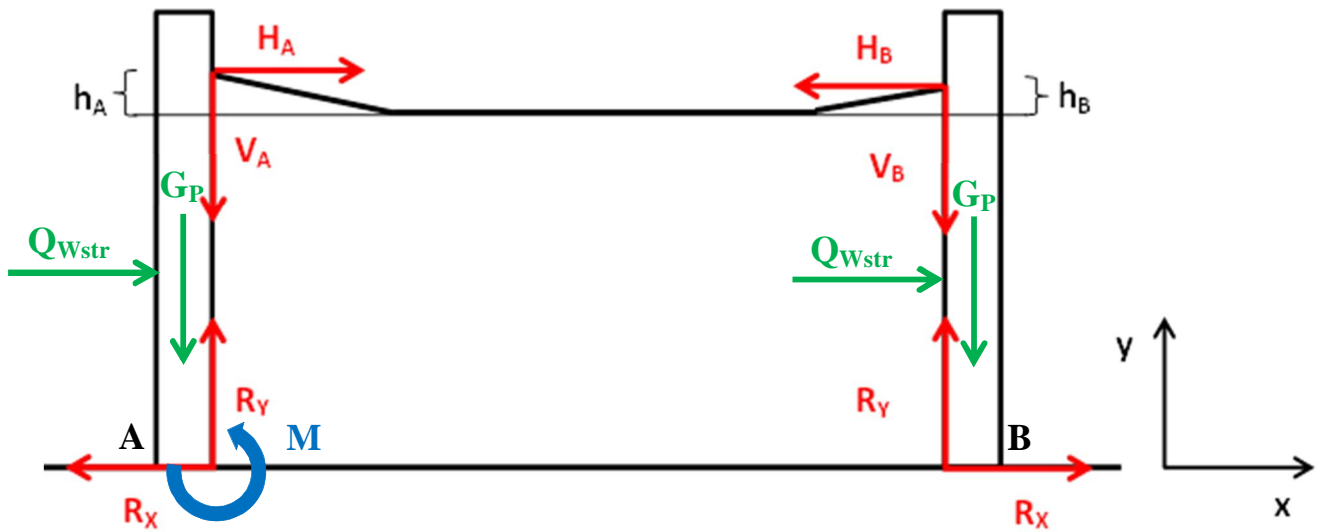


Figure 3.2. Reaction forces at poles

Case A

The following equations have been used for pole A:

$$R_Y = 1,3 \cdot G_P + V_A$$

$$R_X = H_A$$

$$M = H_A \cdot (h_{track} + h_{CW} + h_{CW-cross-span} + h_A)$$

Where G_P is the self-weight of the pole; V_A and H_A are the vertical and the horizontal forces at the support, respectively; h_{track} is the distance between the base of the pole and the track; h_{CW} is the distance between the contact wire and the track; $h_{CW-cross-span}$ is the distance between the contact wire and the cross-span arrangement and h_A is the distance between the point where the cross-span supports the contact wire and the attachment at the pole (as shown in Figure 3.1). R_Y and R_X are the reactions at the base of the pole and M , the moment on the base (as shown in Figure 3.2).

If $G_P = 2354,4 \text{ N}$; $V_A = 247,8 \text{ N}$; $H_A = 3716,8 \text{ N}$; $h_{track} = 0,2 \text{ m}$; $h_{CW} = 6 \text{ m}$; $h_{CW-cross-span} = 0,5 \text{ m}$ and $h_A = 0,4173 \text{ m}$, then $R_Y = 3308,52 \text{ N}$, $R_X = 3716,8 \text{ N}$ and $M = 26453,58 \text{ Nm}$.



Case B (wind from the left)

The following equations have been used for pole A:

$$R_Y = 1,3 \cdot G_P + V_A$$

$$R_X = H_A + 1,3 \cdot Q_{Wstr}$$

$$M = H_A \cdot (h_{track} + h_{CW} + h_{CW-cross-span} + h_A) + 1,3 \cdot 0,5 \cdot h \cdot Q_{Wstr}$$

Where Q_{Wstr} is the wind force acting on the pole and h is the height of the pole.

If $G_P = 2354,4 N$; $V_A = 228 N$; $H_A = 3353,5 N$; $Q_{Wstr} = 3100,9 N$; $h_{track} = 0,2 m$; $h_{CW} = 6 m$; $h_{CW-cross-span} = 0,5 m$; $h_A = 0,4173 m$ and $h = 8m$, then $R_Y = 3288,72 N$, $R_X = 677,66 N$ and $M = 7743,23 Nm$.

Case B (wind from the right)

The following equations have been used for pole A:

$$R_Y = 1,3 \cdot G_P + V_A$$

$$R_X = H_A - 1,3 \cdot Q_{Wstr}$$

$$M = H_A \cdot (h_{track} + h_{CW} + h_{CW-cross-span} + h_A) - 1,3 \cdot 0,5 \cdot h \cdot Q_{Wstr}$$

If $G_P = 2354,4 N$; $V_A = 267,8 N$; $H_A = 4113,2 N$; $Q_{Wstr} = 3100,9 N$; $h_{track} = 0,2 m$; $h_{CW} = 6 m$; $h_{CW-cross-span} = 0,5 m$; $h_A = 0,4173 m$ and $h = 8m$, then $R_Y = 3328,52 N$, $R_X = 8144,36 N$ and $M = 45399,51 Nm$.

Case C

The following equations have been used for pole A:

$$R_Y = 1,3 \cdot G_{P,I} + V_A$$

$$R_X = H_A$$

$$M = H_A \cdot (h_{track} + h_{CW} + h_{CW-cross-span} + h_A)$$

Where $G_{P,I}$ is the weight of the pole with ice.

If $G_{P,I} = 2589,84 N$; $V_A = 393,2 N$; $H_A = 5954 N$; $h_{track} = 0,2 m$; $h_{CW} = 6 m$; $h_{CW-cross-span} = 0,5 m$; and $h_A = 0,4173 m$, then $R_Y = 3759,99 N$, $R_X = 5954 N$ and $M = 42376,4 Nm$.



Chapter 4 CONCLUSIONS AND CONTRIBUTIONS

The city of Wolverhampton, United Kingdom, has been provided with a bus, rail and tram interchange, facilitating the intermodal transport. The design of the overhead contact line for the prolongation of the existing tramway line has been done in accordance with the requirements of the client, international and national standards and best engineering practices.

The provided indications of the extent and requirements of the support systems envisaged to correctly locate and maintain the contact wire are based on the existing infrastructure configurations and the proposed track alignment. As it was preferred to support the OLE with cross-span wires and building fixings, this type of support has been used where possible. Where building fixings were not capable of withstanding the loads or where statutory powers could not be obtained to make fixings to the buildings, dedicated OLE poles or combined OLE and street lighting poles have been used. In this case, the contact wire is supported by cross-span wires, side-bridle arrangements or cantilever arms.

The method used to accomplish the detailed design has been described. This method comprises electrical and mechanical calculations to support the design decisions that have been made. The wires have been selected taking into account the long-term operational load and the short-circuit current, as calculated in Section 3.1. The positions of the supports have been chosen according to the maximum span length that could be achievable, which depends on multiple parameters, such as the tensile forces, the wind load and the radius of the curves. Once the positions were chosen, it should be demonstrated that the loads did not exceed the maximum permitted on wires and, where applicable, on poles. Then, the geometry of the cross-span arrangements, the reaction forces at the supports and the moments on the base of the poles have been calculated, in order to define the position and size of every support, attachment and foundation. All those calculations are developed in Section 3.2.

The followings have been identified as key risks to this OLE design: track alignment and WIP proposals changes, unsuitability of buildings for fixing to and inability to obtain the permission or statutory powers to make fixings to the buildings identified in the layout.

An outline design for the OLE for WCCE is indicated in the following figure. The drawing identifies the contact wire, support wires, cantilever arms and references locations for new poles (numbered in red) and building fixings (numbered in blue).



Figure 4.1. Outline design for the OLE for WCCE



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