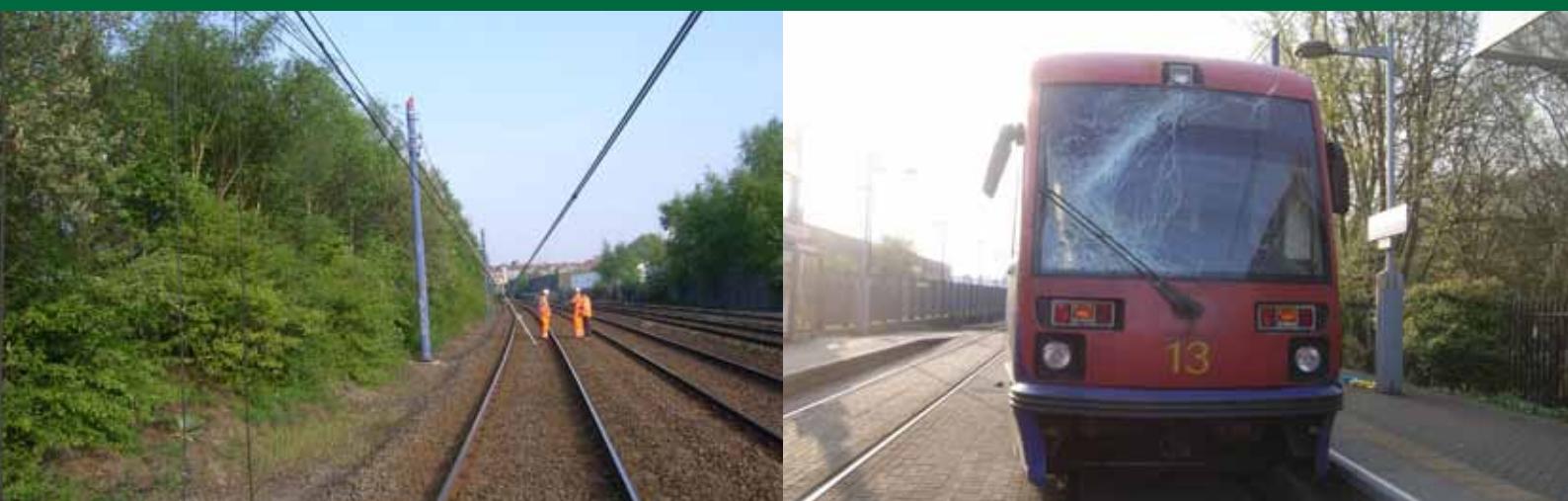




Rail Accident Investigation Branch

Rail Accident Report



**Collapse of the overhead line near to Jewellery
Quarter Tram Stop, Midland Metro
20 April 2011**

This investigation was carried out in accordance with:

- the Railway Safety Directive 2004/49/EC;
- the Railways and Transport Safety Act 2003; and
- the Railways (Accident Investigation and Reporting) Regulations 2005.

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This report is published by the Rail Accident Investigation Branch, Department for Transport.

Collapse of the overhead line near to Jewellery Quarter Tram Stop, Midland Metro, 20 April 2011

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Summary

At 13:25 hrs on 20 April 2011, a tram travelling towards the Jewellery Quarter tram stop on the Midland Metro struck an item of overhead line equipment (OLE), known as a cantilever, which had previously become partially detached from its supporting pole. This damaged the tram and led to a progressive collapse of the OLE for about 200 metres, which resulted in further damage to the tram. Three adult and three child passengers suffered injuries which required hospital treatment as a result of the accident.

The cantilever became detached because part of the assembly which connected it to its supporting pole, known as the reducing sleeve, had fractured after becoming mechanically overloaded.

This overload resulted from a combination of the cantilever becoming momentarily restrained at some point along its length and either the introduction of an abnormal load (following the failure of a tensioned component) or the action of operating loads within the OLE. The cantilever may also have been restrained to some degree from rotating around its supporting pole. This restraint, the way in which the cantilever was installed, the ambient temperature and reduced clearances around tensioned components were also possibly factors in creating the overload.

The RAIB has made seven recommendations to National Express Midland Metro. These cover;

- the understanding of relevant failure mechanisms within the OLE system and the prevention of further similar incidents;
- the change control of safety critical OLE components;
- the management of the possible risks created by a driver becoming incapacitated during an incident; and
- the maintenance of mandatory competences held by members of tram crew.

Introduction

Preface

- 1 The purpose of a Rail Accident Investigation Branch (RAIB) investigation is to improve railway safety by preventing future railway accidents or by mitigating their consequences.
- 2 The RAIB does not establish blame or liability, or carry out prosecutions.

Key definitions

- 3 All dimensions and speeds in this report are given in metric units.
- 4 The report contains abbreviations and technical terms (shown in *italics* the first time they appear in the report). These are explained in appendices A and B.

The accident

Summary of the accident

- 5 At 13:25 hrs on 20 April 2011, Midland Metro Tram No. 13, the 13:05 hrs service from Wednesbury Parkway to Birmingham Snow Hill, struck a *cantilever* forming part of the *overhead line equipment* (OLE) whilst on the approach to the Jewellery Quarter tram stop, on the Midland Metro tramway in Birmingham. The cantilever had become partially detached from its supporting pole prior to the arrival of the tram.

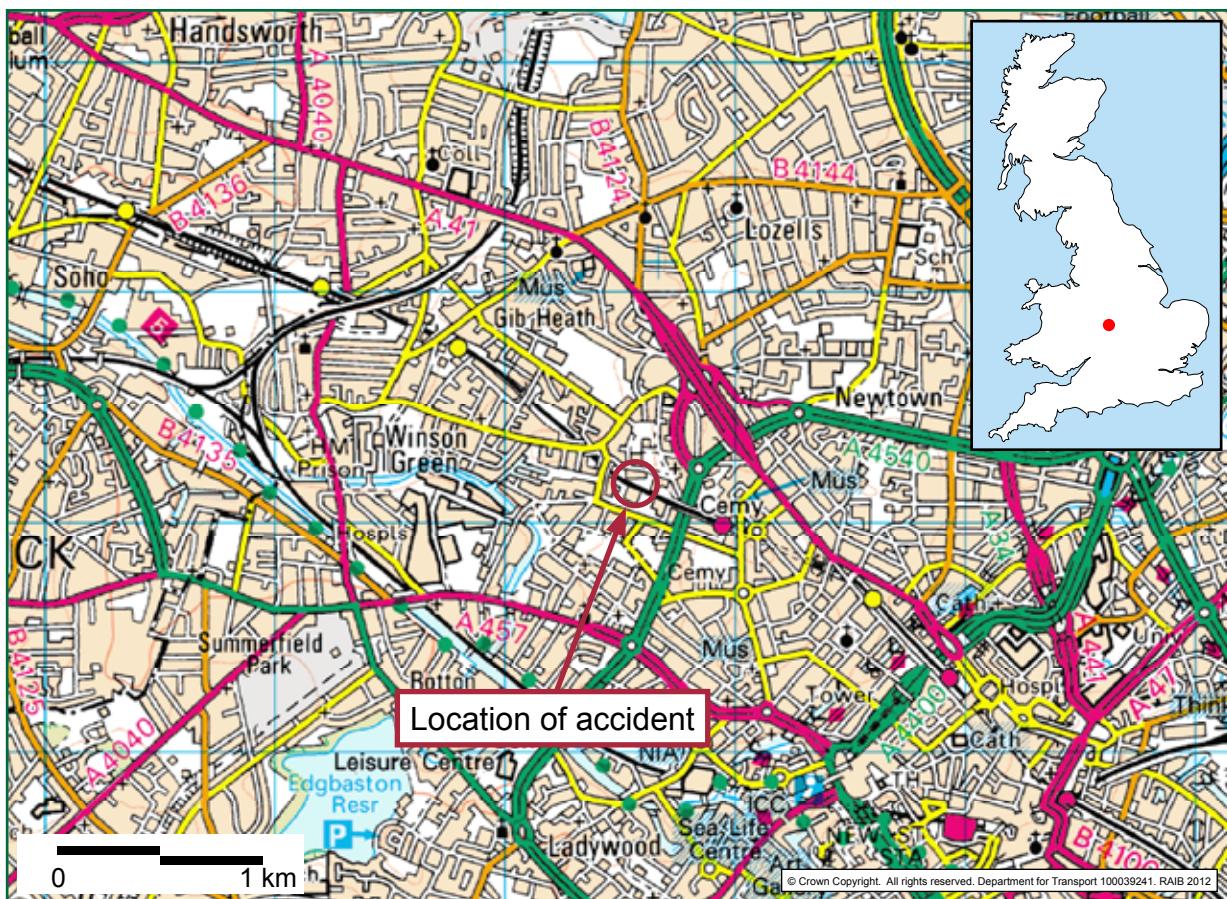


Figure 1: Extract from Ordnance Survey map showing location of accident

- 6 The striking of the cantilever caused severe damage to Tram 13's *pantograph* and led to a progressive collapse of the OLE for about 200 metres. This caused further cantilevers to become partially or fully detached from their poles and to be struck by Tram 13, causing damage to the tram's front and rear windscreens, to side windows in the driver's cab and passenger saloon and to the tram's doors.
- 7 The driver brought the tram to a stand at the Jewellery Quarter tram stop, where the passengers were able to exit onto the platform. Of the two crew members and approximately twenty passengers onboard the tram, three adult and three child passengers suffered injuries which required hospital treatment.

- 8 Following the accident the tramway remained closed for repairs between the Jewellery Quarter and Soho Benson Road tram stops until 24 April 2011, when a limited service resumed. The tramway re-opened for normal service on 28 April 2011.

Location

- 9 The Midland Metro provides a tram service between Wolverhampton St. George's and Birmingham Snow Hill tram stops. The route is twenty kilometres long, separated into sections of *on-street* and *off-street* running.
- 10 The cantilever that was struck by Tram 13 was at OLE pole 18512, which is located around 230 metres to the Wolverhampton side of the Jewellery Quarter tram stop. The tramway at this point is segregated from the highway and runs on a former railway track bed. It has a double track configuration, with the Birmingham line to the north and the Wolverhampton line to the south (figure 2). The incident tram was travelling towards Birmingham on the Birmingham line when the accident occurred. On this part of the network trams operate on a *line-of-sight* basis.
- 11 At this location, the Birmingham line runs adjacent to the tramway cess and boundary fence. South of the Wolverhampton line, and separated from it by a *ten foot*, is a double track railway line within the control of Network Rail. 18512 pole is situated in the tramway cess approximately 260 metres into a 349 metre long, 1200 metre radius, left-hand curve in the track. At the time of the accident, there was a maximum permitted speed for trams of 70 km/h at this location, reducing to 30 km/h on the immediate approach to the tram stop.

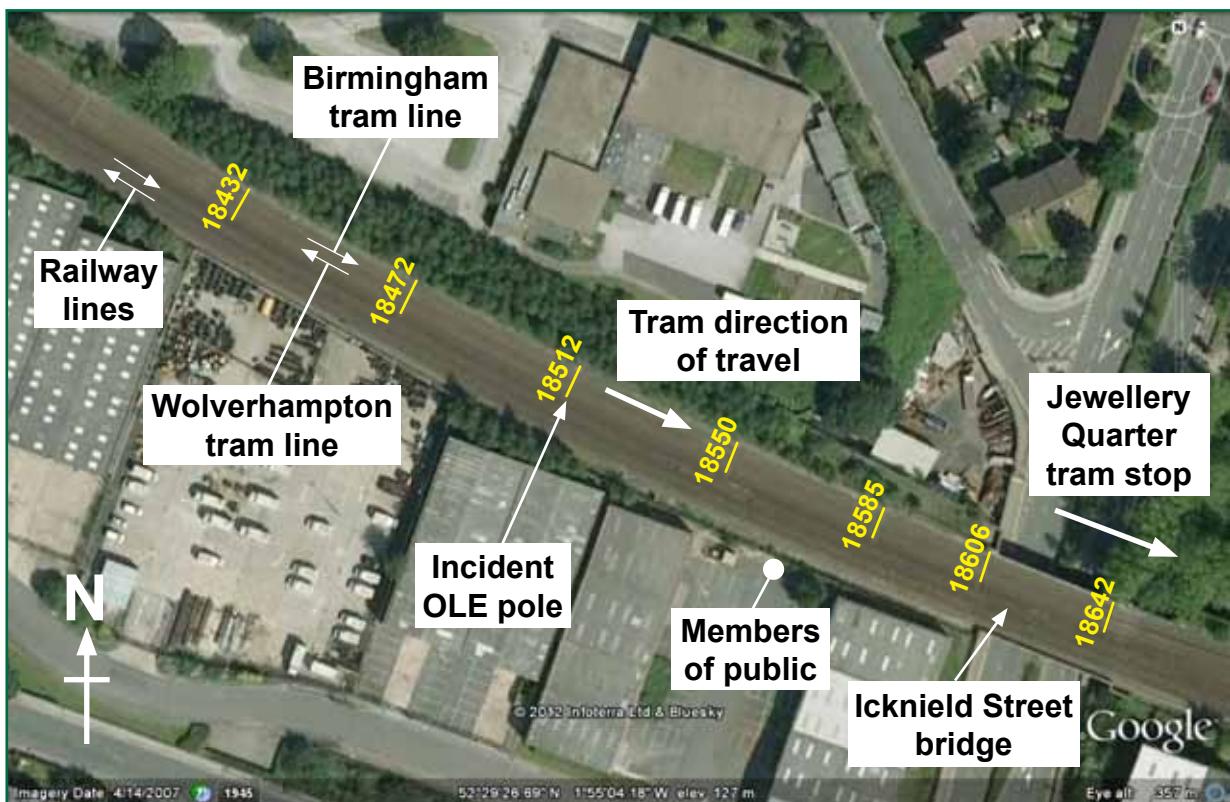


Figure 2: Layout of tram and railway tracks, showing the location of OLE poles and witnesses

Organisations involved

- 12 The West Midlands Passenger Transport Executive and Authority (known as 'Centro') are the owners of the Midland Metro tramway system. The operation and maintenance of the network is contracted via a long-term concession to National Express Midland Metro (NXMM - formerly known as Travel Midland Metro). Senior staff within NXMM are employees of its parent company, National Express West Midlands (NXWM - formerly known as Travel West Midlands).
- 13 Brecknell Willis is a company specialising in the electrification of transport systems. It was responsible for the original design, manufacture and installation of the OLE system in the 1990s, whilst under contract to a company forming part of the original concessionaire¹ for the Midland Metro. It was also contracted by NXMM to provide technical and inspection support for modifications undertaken to the OLE in October 2010 and April 2011.
- 14 VolkerRail Power (formerly known as Grant Rail Power) was the electrification company contracted by NXMM to provide on-call labour and machinery for emergency OLE repairs between September 2007 and October 2010.
- 15 Keltbray Aspire was the electrification company contracted by NXMM to undertake modifications to the OLE in October 2010 and April 2011. It also undertook repairs of the OLE system following the accident.

The Tram

- 16 Tram 13 is an AnsaldoBreda T69 type tram which consists of 2 cars, joined by an articulated section at the centre of the tram. The tram was being driven from its 'B' end driving cab at the time of the accident, with its single pantograph raised at the 'A' end (the trailing end of the tram in the direction of travel - see figure 3).
- 17 The trams' driving cabs are separated from the passenger saloon by a partition, the upper half of which is fitted with glass screens. The driving cab is normally accessed from the saloon via the cab door, which is fitted with a window (figure 4). This door is kept locked when the tram is in service. The driving cab also has side windows which can be used to gain access to it from outside in an emergency.
- 18 The pantograph of Tram 13 is of a single arm type, manufactured by Brecknell Willis. It is raised and maintained in its running position via an electrical actuator and spring force. The lower and upper arms of the pantograph are made up of steel box sections. The pantograph head consists of an aluminium carrier fitted with carbon contact strips.
- 19 Tram 13 has a windscreen constructed of laminated glass. A post-incident survey of the saloon windows and door glazing panels which remained intact following the accident showed that they were all fitted with toughened glass; this type of glass was also specified for use in the driving cab partition screens. This indicates that the glazing fitted to the tram at the time of the accident very probably met or exceeded the requirements of the applicable guidance².

¹ The concession for the Midland Metro was originally awarded to Altram LRT Ltd. This was a joint venture, which included National Express West Midlands amongst its constituent companies. National Express West Midlands took effective sole control of the running of the metro from 2001 and bought out the remaining joint-venture shares in March 2006.

² Office of Rail Regulation, Railway Safety Publication No. 2 'Guidance on Tramways', 2006, formerly published as Railway Safety Principles and Guidance (RSPG) Part 2 Section G 'Guidance on Tramways'; a draft copy of this formed the technical note which formed the basis of the approval of the Midland Metro into commercial service.



Figure 3: Damage to the trailing end of tram 13 (image courtesy of National Express Midland Metro)



Figure 4: Damage to the saloon interior at the leading end of Tram 13 - the cab door is shown in the open position (image courtesy of National Express Midland Metro)

Staff

- 20 The tram crew consisted of a driver and a *customer service representative* (CSR) who was in the saloon at the time of the incident. Drivers receive training in dealing with OLE incidents, in the emergency evacuation of passengers from trams and in acting as the *primary member of service* (PRIMOS) at incidents. The PRIMOS is the NXMM member of staff who will take charge of an incident on behalf of the tramway and liaise with other agencies pending the arrival of an *Incident Officer*. Drivers can make contact with Metro Control using the tram's integrated cab radio.
- 21 The role of a CSR is primarily to give information to passengers and to collect revenue. During their initial training CSRs are not trained to evacuate trams, to deal with OLE incidents or to act as PRIMOS, although some CSRs opt to be trained in these areas later during professional development days. The CSR on board Tram 13 on 20 April 2011 had not undertaken this training. During emergencies CSRs are instructed to keep passengers onboard the tram if possible, to calm them and try to determine if anyone is injured. During emergencies CSRs are expected to look to the driver for instructions.
- 22 At the start of each shift, the driver of a tram is issued with a tram kit which includes a hand-portable radio. This is intended for use by the CSR so that they can contact Metro Control if needed. The CSR involved in the incident had been trained in the use of the radio but was not carrying it at the time of the accident. Witness evidence is that it was common practice for CSRs (who were already required to carry a ticket machine and a cash bag) to leave this radio in one of the cabs due to its size and weight. At the time of the accident, CSRs were not equipped with keys for the driving cab doors.

Overhead Line Equipment (OLE)

- 23 Traction power on the tramway is provided by OLE energised at 750V DC. For the majority of the segregated section, the OLE has two copper *contact wires* per track, each with a 150 mm² cross sectional area³. Once positioned above the track, both contact wires are clamped together, giving a total cross sectional area of 300 mm². This ensures that the electrical resistance of the contact wire is sufficiently low to maintain the required traction voltage.
- 24 Each twin contact wire is suspended from a *headspan*, *span-wire* or *bracket arm*. The section of OLE involved in the accident was of the bracket arm type which is based around a steel tubular cantilever (figure 5). This is adjusted in height so that the contact wires will contact the pantograph of trams. Around 18512 pole, the *wire-height* was approximately 5.3 m above rail level. The contact wire is suspended approximately 415 mm below the cantilever via a contact wire *delta suspension* (also known as a bridle) made of a type of *aramid fibre* rope called *Parafil*. This 7 mm diameter rope is held at its apex either within a clamp or allowed to run freely over a plastic pulley (paragraph 80). Both clamp and pulley connect to a bracket on the cantilever via shackles and/or quick links.

³ The contact wires meet the nominal dimensions for the AC150 type of contact wire defined within BS EN 50149:2001 *Railway applications. Fixed installations. Electric traction. Copper and copper alloy grooved contact wires*.

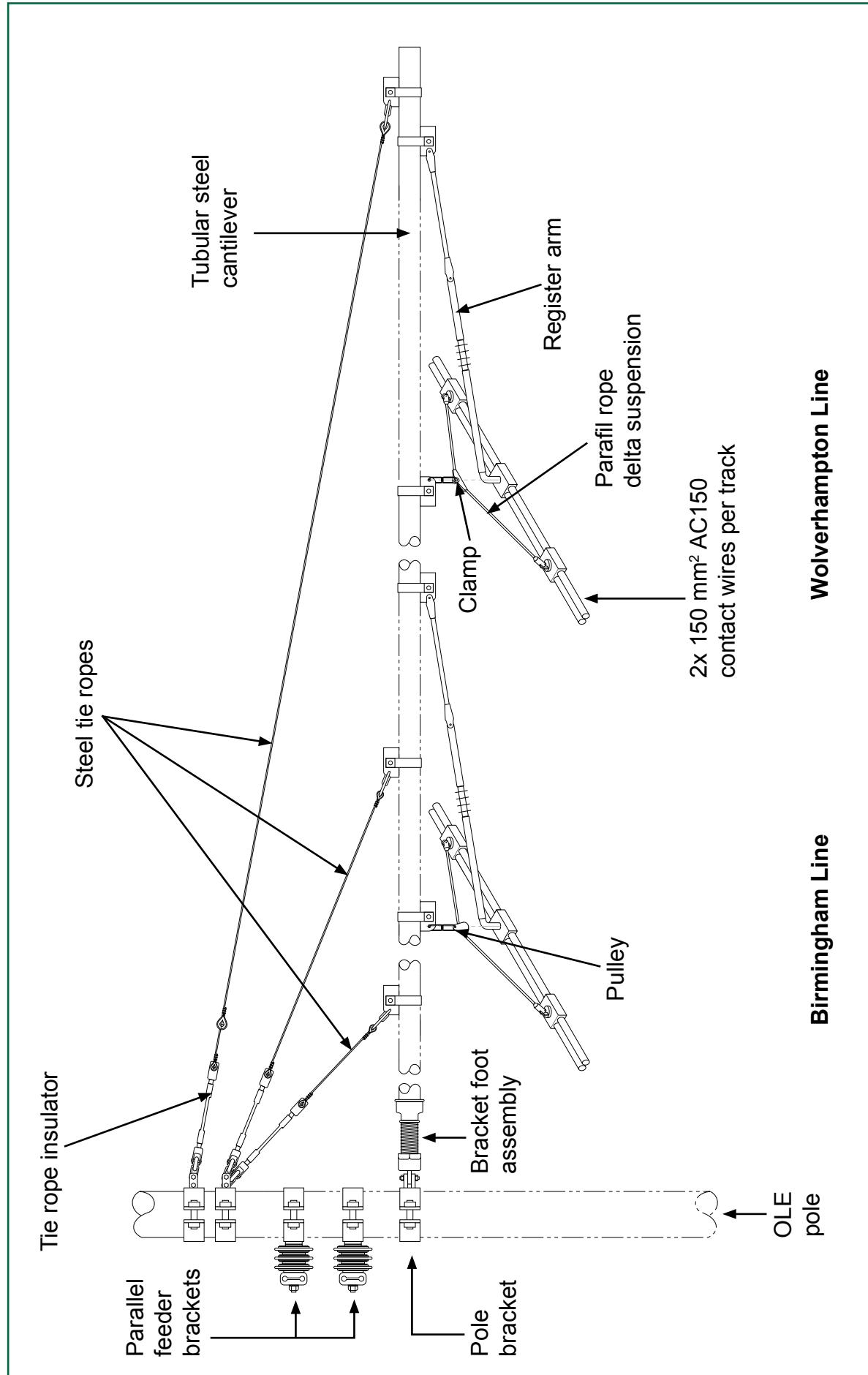


Figure 5: Twin-track bracket arm assembly

- 25 Each twin contact wire is connected to a *register arm* (also known as a steady arm) which is also connected to the cantilever. This arm allows the wire to lift under the force of a pantograph whilst maintaining it in the correct lateral position above the track (known as *register*). Register is intentionally varied with respect to the centre line of the track so that the contact wire sweeps across the width of pantograph heads and wears them evenly; this is known as *stagger*.
- 26 In other parts of the network there is a separate bracket arm for each track, supported by OLE poles at either side of the tramway. However, on the approach to the Jewellery Quarter tram stop the proximity of the railway meant that it was necessary for the Birmingham and Wolverhampton contact wires to both be suspended from a single, longer, tubular cantilever connected to an OLE pole in the tramway cess adjacent to the Birmingham line. This arrangement is known as a twin track bracket arm.
- 27 The cantilever of the twin track bracket arm is attached to the OLE pole using one of several types of *pole bracket* (paragraph 35). All of the pole bracket types have a *clevis* and use a pin to connect to the cantilever's *bracket foot assembly* (figure 6). This assembly is made up of;
- an aluminium bronze *clevis cover*, the *tang* of which fits into the clevis of the pole bracket and is held in position by the *clevis pin* (figure 20);
 - a nylon threaded *insulator* which screws into the clevis cover at one end and into the reducing sleeve at the other end; and
 - a cast aluminium alloy *reducing sleeve*, which has internal threads that will accept the insulator (at its smaller diameter end) and the thread cut into the exterior of the cantilever tube (at its larger diameter end).



Figure 6: Bracket foot assembly

- 28 The cantilever is supported from above by *tie ropes* which bear the majority of the vertical load. These attach to tie rope brackets on the OLE pole (figure 7). There were originally two Parafil tie-ropes fitted to all of the cantilevers between 18302 and 18512 poles. However, following a dewirement in August 2009 (paragraph 51), these were replaced by three steel tie ropes as part of a trial to improve the resilience of the OLE system. These were in turn replaced with three steel tie ropes of another design as part of an OLE modification programme in October 2010 (paragraph 52); it was these tie ropes which were in place at the time of the accident in April 2011. Following the accident, four steel tie ropes were fitted to the twin track bracket arm assemblies damaged in the accident, including that at 18512 pole.

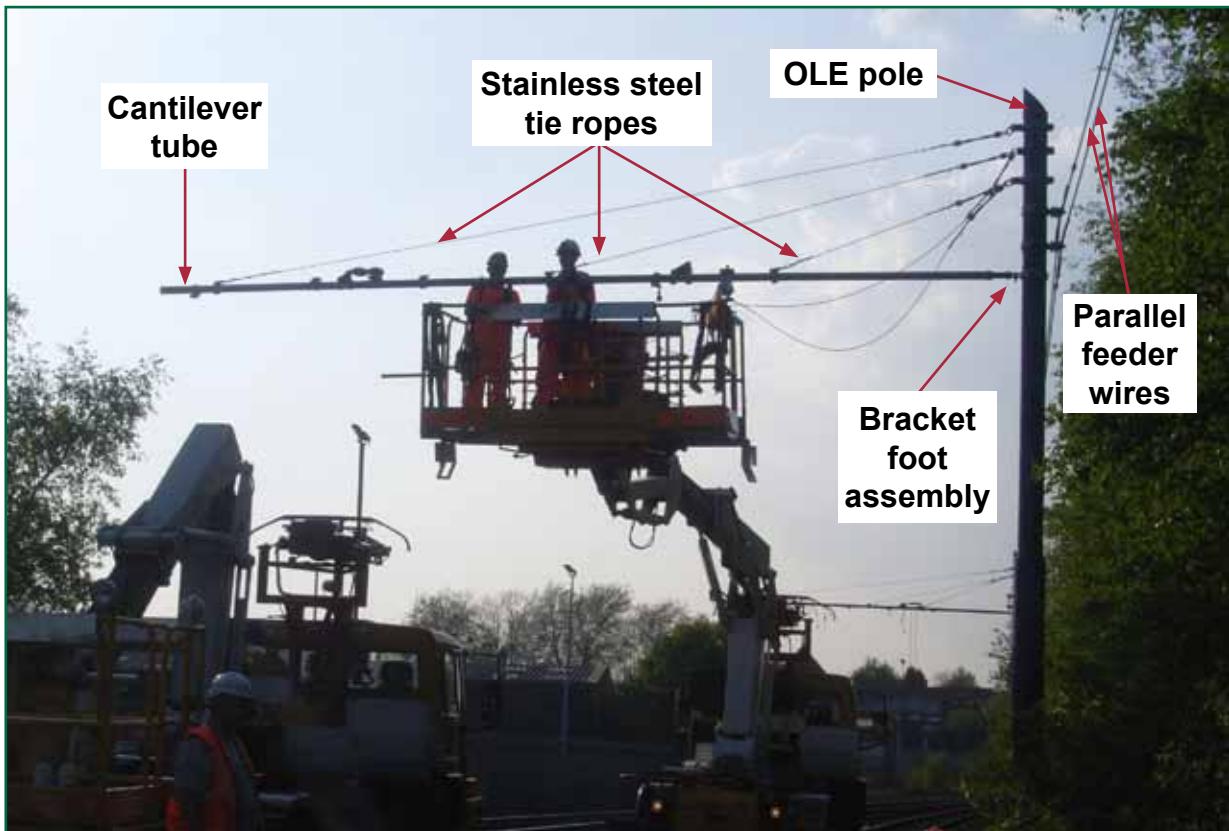


Figure 7: Tie ropes (shown during the re-installation of a cantilever following the accident)

- 29 Within the majority of the segregated section, each contact wire is mechanically tensioned to 15 kN (ie 30 kN per track). Tensioning is achieved by having a nitrogen gas *auto-tensioner* situated at one end of a length of wire, with the other end being fixed via a running rope to an anchor on an OLE pole. The same auto-tensioner will connect to both contact wires for a particular track. A section of wire running between a tensioner and anchor point is known as a *tension length*.
- 30 Contact wires are tensioned to permit the wave created by the vertical upwards force of the pantograph to travel along the wire faster than the speed of the tram. This ensures smooth passage of the pantograph and an uninterrupted power supply. The tension needed relates to the mass of the contact wire, with heavier wires requiring higher tensions. 30 kN is a relatively high contact wire tension - this reflects the relatively high mass of the contact wire in this section of the tramway. In comparison, contact wires on other UK tramways normally have a tension of 12 kN or less per track.

- 31 In order to further increase the effective cross-sectional area of the contact wire (and thus reduce its electrical resistance) additional along-track conductors known as *parallel feeder wires* (or aerial feeders) are fitted. These wires were originally supported on the cantilevers but were remounted directly onto the OLE poles as part of the October 2010 modification programme (paragraph 52). The feeder wires are clamped in place and the tension within them varies as they expand and contract due to changes in temperature.
- 32 18512 pole forms part of the change-over point between two adjacent tension lengths, known as an *overlap*. At an overlap the *out-of-running* contact wire (the tension length terminating with respect to a particular direction of travel - in this case, towards Birmingham) rises vertically so that pantographs are no longer in contact with it. Simultaneously the *in-running* contact wire (the tension length which is commencing) descends into the running position, thus maintaining a continuous supply of traction power to the tram. A diagram of the overlap arrangement between 18472 and 18512 poles is shown in figures 8 and 9.

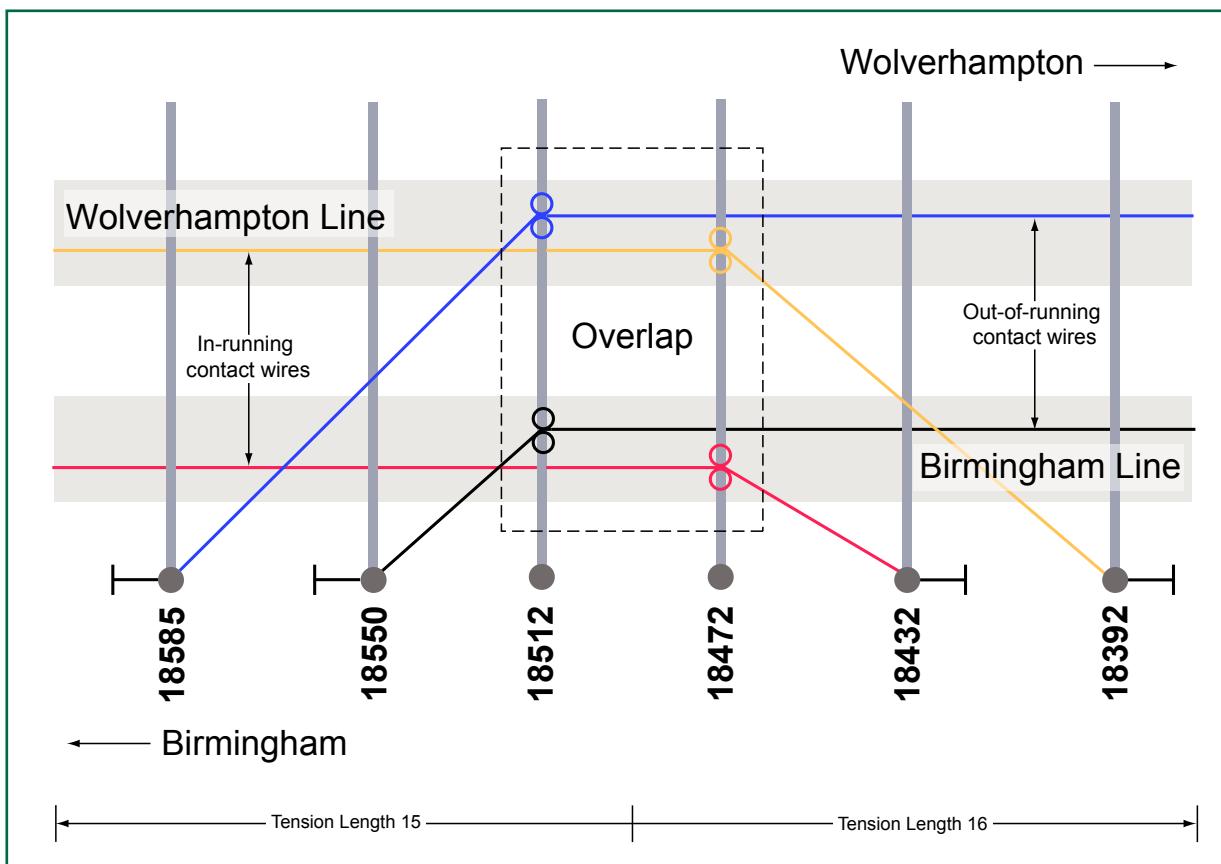


Figure 8: Diagram of change over between tension lengths 15 and 16 (plan view)

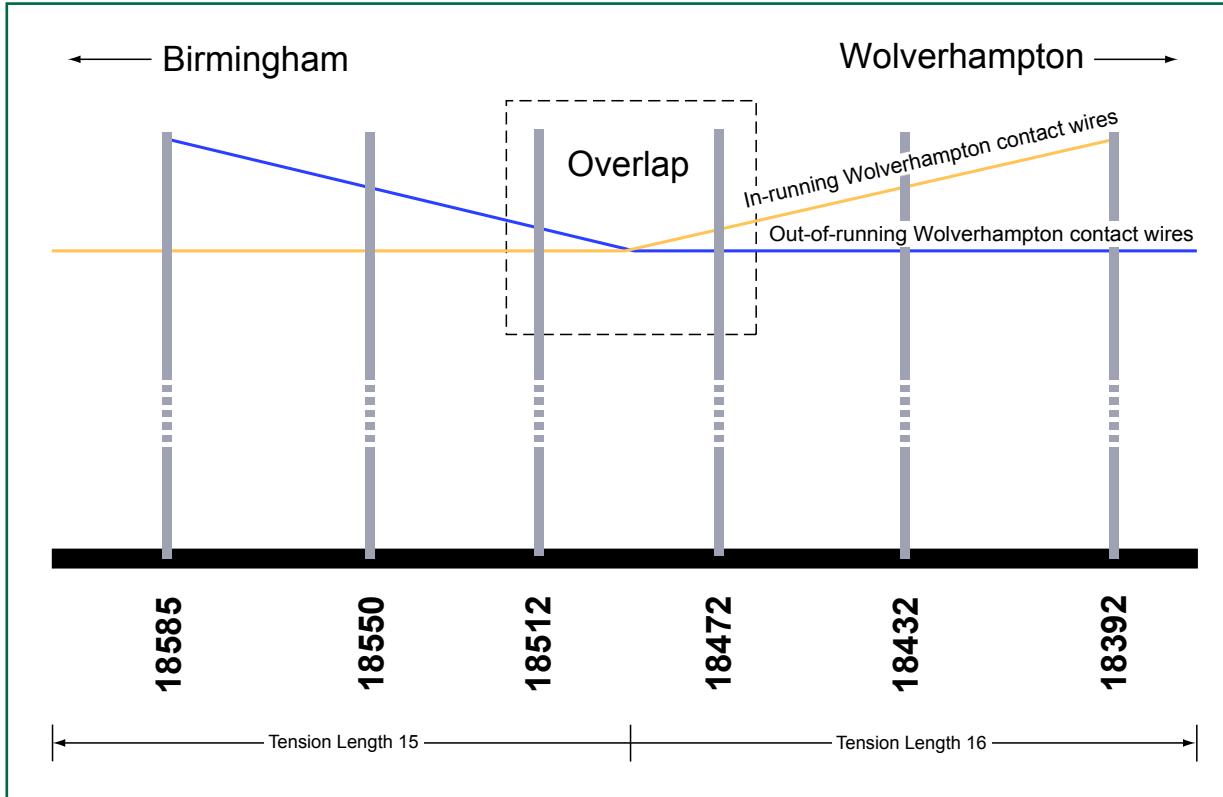


Figure 9: Diagram of change over between tension lengths 15 and 16 (elevation looking south towards Wolverhampton line)

- 33 Further detail of the overlap between 18472 and 18512 poles is shown in figures 10 and 11. The in-running contact wires start at anchor points on the OLE poles, situated above the cantilevers. 11 mm diameter Parafil ropes, one per contact wire, connect to these anchors and descend gradually in height before connecting to short lengths of stainless steel rope which pass through the four in-running pulleys. These pulleys lie just above, and are fixed to, the cantilever situated immediately on the approach to the overlap (18472 pole). On leaving the pulleys, there are further short lengths of Parafil which then connect to the contact wires proper. These descend to the running position around the mid-point between the cantilevers. The out-of-running contact wires follow the same arrangement but in reverse. The gas tensioners are situated at the other end of the tension lengths.
- 34 Twin track bracket arms are subjected to higher loads at overlaps due to the extra equipment fitted and the additional load created by the in-running and out-of-running ropes (paragraph 75). Because of this, cantilevers at overlaps have a 10 mm wall thickness instead of the normal 3 mm wall thickness found elsewhere. The outside diameter of the cantilever is constant regardless of the wall thickness and a common bracket foot assembly is used for both types.
- 35 The pole bracket type originally fitted at 18512 pole used a malleable iron clevis which was attached to the pole using stainless steel straps (figure 20). Because of concerns relating to the bracket's reliability, NXMM replaced this type of bracket, where the opportunity arose, with one entirely fabricated from steel (figures 19 and 21). This second design was based on that of a bracket already in use to fix tie ropes to OLE poles but which had a square faced clevis. This was modified so that the profile of the clevis became rounded. In some cases, including during post-accident repairs, tie rope brackets had their square clevis rounded off by grinding so that they could be used in place of this second type of pole bracket.

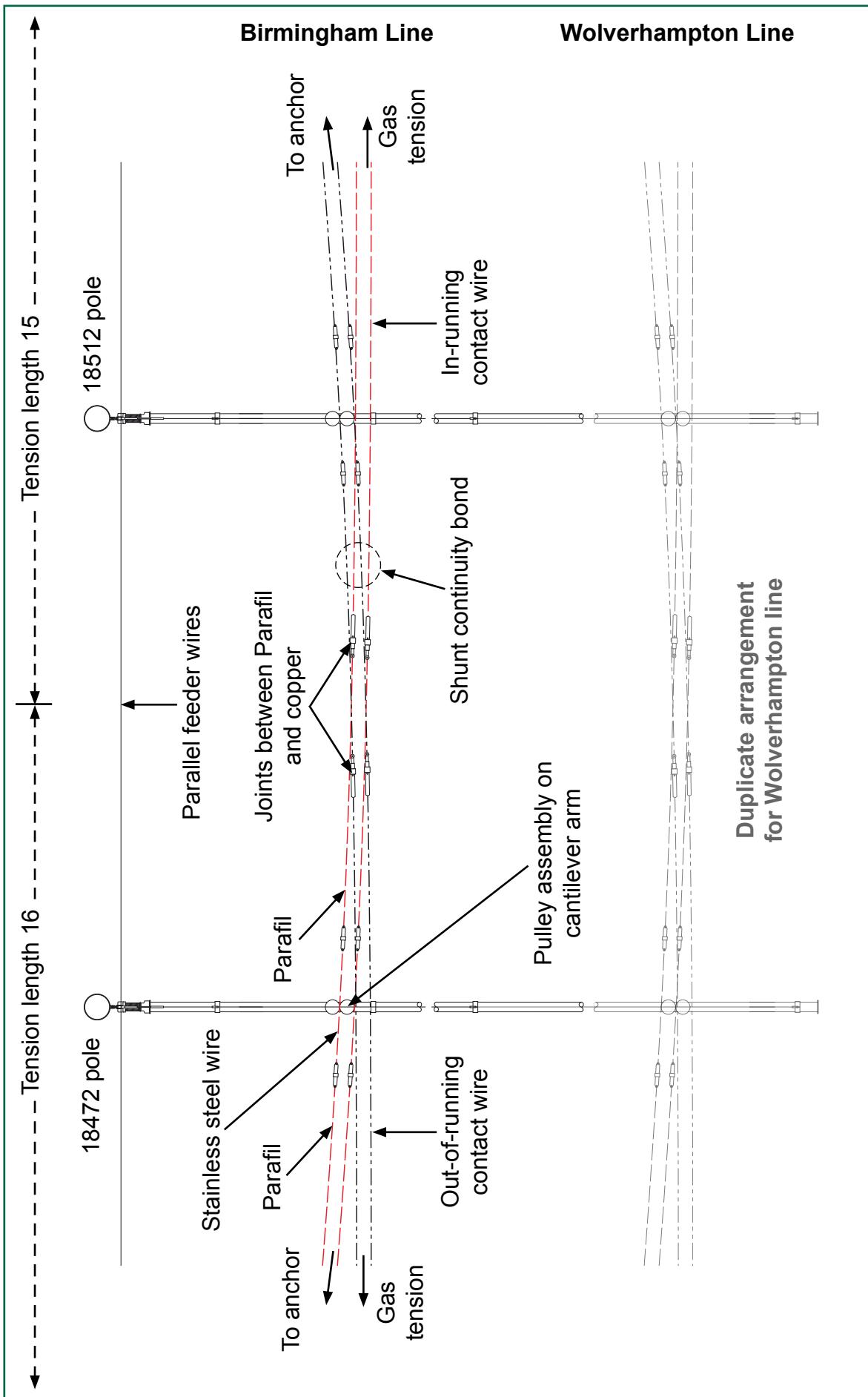


Figure 10: Diagram of change over between tension lengths 15 and 16

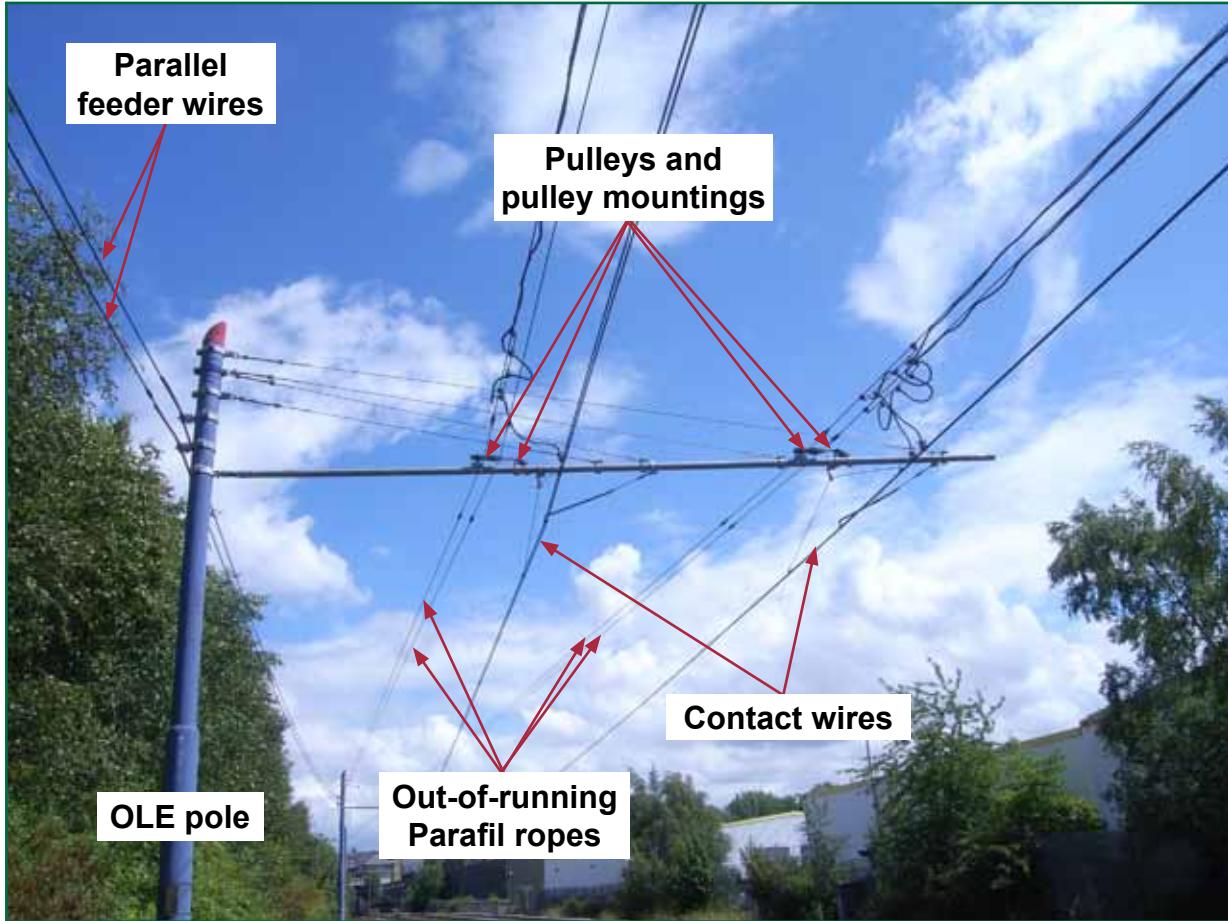


Figure 11: Post-incident photograph of overlap equipment at 18512 pole

External circumstances

- 36 The weather on the day of the incident was sunny. As on the previous day, there was a maximum ambient temperature of 21 °C. The mean wind speed was around 6 km/h, a light breeze. The possible role of weather in the accident is explored in paragraphs 70 and 87.

Events preceding the accident

- 37 Just before 13:00 hrs the tram driver and CSR signed-on at the Metro Centre at Wednesbury. At 13:06 hrs they took over as the crew of Tram 13 at Wednesbury Great Western Street tram stop and the tram then departed on the Birmingham Line towards the Birmingham Snow Hill terminus.
- 38 At 13:17 hrs platform CCTV recorded Tram 4 stopping at the Jewellery Quarter tram stop, on its way towards Birmingham Snow Hill. This was the last tram to pass on the Birmingham line prior to the arrival of Tram 13. The same CCTV recorded Tram 5 stopping on its way towards Wolverhampton at 13:18 hrs.
- 39 At 13:20 hrs the platform CCTV at the tram stop recorded the start of large movements in the contact wires on both lines. This was the result of the cantilever at 18512 pole becoming partially detached. The movements continued at a lesser magnitude until the accident, probably because the contact wires were now to some extent supporting the cantilever.

- 40 At the same time two members of the public who were standing in a car park adjacent to the Network Rail lines (figure 2) heard a loud noise come from the direction of the tramway and noticed that the OLE was moving violently. Looking towards Wolverhampton they saw that the cantilever of 18512 pole had 'snapped' and dropped lower than the other cantilevers, whilst remaining horizontal. No trams were present when this occurred.
- 41 These members of the public then called the police using the 999 system to report what had happened. This call was logged at 13:25 hrs⁴ by the West Midlands Police. However, whilst the call was in progress, Tram 13 arrived and struck the detached cantilever.

Events during the accident

- 42 At 13:24:57 hrs the tram CCTV system (which has cameras facing forwards and rearwards through cab windscreens and also throughout the saloon) shows Tram 13 approaching 18512 pole. The detached cantilever was not seen by the driver and was also out of view of the CCTV. The tram's onboard *data recorder* registered its speed as being 70 km/h at this point.
- 43 At 13:24:59 hrs the tram CCTV system records the rear windscreen fracturing as it passed under the cantilever at 18512 pole; it also shows passengers reacting immediately afterwards to a noise at the rear of the tram. The separated pantograph was found lying near to this point after the incident. This indicates that it was the collision of the pantograph of Tram 13 with the cantilever which initiated the ensuing dewirement.
- 44 By 13:25:02 hrs the tram CCTV system recorded the right-hand side saloon doors sustaining damage. It also shows that the OLE collapse had now overtaken the tram, with the cantilever at 18606 pole having detached and dropped in front of the windscreen of the tram's leading cab, which it then struck. Immediately afterwards the front-most right-hand side saloon window and the right-hand side driving cab partition screen both shattered, showering the passenger saloon with glass.
- 45 During the accident the CSR moved throughout the saloon and tried to both reassure passengers and to move them away from danger. The tram driver remained at the controls of the tram, although his windscreen and side window were severely damaged. He decided not to apply the tram's *hazard brake* and to instead control the tram so that it would roll slowly into the tram stop less than 200 m away, where it would be clear of the immediate danger and the passengers could be safely evacuated.

⁴ Police call logs are normally created after the police communications officer has gathered some basic data regarding an incident, so it is likely that the call was made a few minutes before it was logged.



Figure 12: Damage to front windscreens and cab side window of Tram 13



Figure 13: Damage to saloon window and driver's screen glass on the right-hand side leading end of Tram 13

Events following the accident

- 46 Immediately after the tram came to a stand, the tram driver made an emergency call to Metro Control to report the accident and to confirm that the OLE was electrically isolated so that it was safe to open the tram doors and initiate an emergency evacuation of the tram. The CSR, who at this point was standing near to the centre of the tram, was concerned that the driver had become incapacitated during the accident because the saloon doors had not been opened and he could not see the driver through the driving cab partition screen (his view of the cab was probably obscured by passengers moving away from the glass and dust which had entered the front part of the saloon).
- 47 Because he was unable to see the driver from inside the tram, the CSR decided to use an emergency door release⁵ to open a saloon door and exit onto the platform. From here he would be able to check on the driver via the side window of the driving cab and establish if he had been able to contact Metro Control to report the accident. Although not specifically trained in tram evacuation or in managing OLE incidents the CSR was aware from his training that opening a door might cause the passengers to leave the tram where they could possibly be endangered by live OLE components.
- 48 Despite this the CSR felt he had no choice but to leave the tram in order to check on the driver. Having opened the door and left the saloon he instructed at least one passenger to remain inside; some passengers nevertheless decided to leave the tram and follow him onto the platform. The OLE collapse had stopped around 80 metres short of the tram stop; this meant that there was no live equipment in a position which could have endangered these passengers.
- 49 Having exited onto the platform the CSR was able to contact the driver, who had by then confirmed that the OLE was isolated and opened the remaining saloon doors. The driver had also requested the attendance of the emergency services, who arrived a few minutes later. The CSR and driver then assisted passengers in completing the evacuation of the tram, with the driver assuming the role of PRIMOS.

⁵ Emergency door release handles are situated by saloon doors and their location and instructions for use are clearly signed. The use of a release will open only the doors adjacent to the handle. They are intended for emergency use by either NXMM staff or passengers.

The investigation

Sources of evidence

50 The following sources of evidence were used:

- interviews with witnesses;
- CCTV footage from the Jewellery Quarter tram stop and Trams 4 and 13;
- output from the tram's onboard data recorder;
- site photographs, measurements and observations;
- historical weather data;
- the results of a metallurgical examination of OLE components;
- a review of a report commissioned by the RAIB in which an expert in OLE systems reviewed the possible causes by which the cantilever at 18512 pole could have become partially detached;
- the available information regarding previous OLE incidents and historic reliability issues on the Midland Metro;
- Brecknell Willis documents and information relating to the installation of the OLE system on the Midland Metro, OLE component data, the October 2010 OLE modifications and the post-incident testing of bracket foot assemblies;
- VolkerRail Power documents relating to the undertaking of emergency OLE repairs on the Midland Metro between September 2007 and October 2010;
- Keltbray Aspire documents relating to the October 2010 OLE modifications and the repairs to the system following the accident;
- calculations and Finite Element Analysis relating to the loads acting on the bracket arm at 18512 pole; and
- Midland Metro documents relating to the training of CSRs and risk assessments and procedures relating to the emergency evacuation of trams.

Key facts and analysis

Background information

- 51 In August 2009, the OLE between 18302 and 18512 poles underwent significant repair work following a dewirement. The repair included fitting a modified type of pole bracket (paragraph 35), an aluminium alloy reducing sleeve (paragraph 27) and the replacement of the existing Parafil tie ropes with a type of steel tie rope (paragraph 28).
- 52 Following this incident and dewirements at other locations, the OLE within the southern part of the network (which included the Jewellery Quarter tram stop and its approaches) went through a modification programme in October 2010 which was intended to reduce vertical loads and so reduce the number of failures. Work undertaken included the removal of the parallel feeders from the cantilevers and their mounting onto the OLE poles, replacement of all existing tie ropes with a new type of steel tie rope and an increase in the number of tie ropes supporting twin track bracket arms in some locations. The northern part of the network was closed when the accident occurred in order to allow it to undergo the same modifications. This closure played no role in the accident.

Identification of the immediate cause⁶

- 53 The immediate cause of the accident was the collapse of the overhead line due to Tram 13 striking the cantilever at 18512 pole.**
- 54 Tram 13 struck a cantilever which had previously become partially detached from 18512 pole. The OLE was not able to tolerate this impact and a progressive collapse and dewirement over about 200 metres resulted. Further cantilevers became fully or partially detached from their poles during this collapse and were also able to collide with the tram. It was these consequential collisions which caused both the injuries to the passengers and the majority of the damage sustained by the vehicle.
- 55 Guidance and advice on the safety of OLE on tramways in Great Britain is provided by the *Office of Rail Regulation* (ORR)⁷. This guidance states that OLE should be designed so that the loss of an overhead line support (such as an OLE pole) in an off-street section may allow the contact wire to sag, provided it remains out of reach of pedestrians. It also states that the connection between an OLE pole and the contact wire (such as a delta suspension) should be mechanically weaker than the contact wire system, to ensure that, if a pole is damaged, then its connection to the OLE will break before the contact wire is dragged down.

⁶ The condition, event or behaviour that directly resulted in the occurrence.

⁷ Office of Rail Regulation, Railway Safety Publication No. 2 ‘*Guidance on Tramways*’, 2006, formerly published as Railway Safety Principles and Guidance Part 2 Section G ‘*Guidance on Tramways*’. Although published after the design, construction and approval into service of this tramway, a draft copy of RSPG Part 2 Section G in the form of a technical note was used as the basis for it to be approved by Her Majesty’s Railway Inspectorate on behalf of the Secretary of State.

- 56 In 2009, an update of European standard BS EN 50119:2009⁸ relating to OLE systems was published. This standard requires that new systems should not have structures within them which are liable to progressive collapse if a component fails. The Midland Metro was designed and approved for service prior to this standard being issued.
- 57 There is nothing within either the ORR guidance or the latest European standard that requires an OLE system to withstand a vehicle striking a component without a progressive collapse occurring.
- 58 The OLE demonstrated a level of resistance to collapse during this accident which was in line with the guidance and requirements in force at the time of the system's design and construction and also those of the current relevant standard.
- 59 The pantograph of Tram 13 is not fitted with an *automatic dropping device* or other similar protection. A device of this type would not have prevented the initial impact which took place between the cantilever at 18512 pole and Tram 13's pantograph; it has not been possible to determine if it would have reduced the extent of the dewirement or the damage which the tram subsequently sustained.

Identification of causal factors

- 60 **The cantilever at 18512 pole collided with Tram 13 because it had previously become partially detached from its OLE pole.**

Partial detachment of the cantilever at 18512 pole

- 61 **The partial detachment of the cantilever at 18512 pole was due to the fracturing of the reducing sleeve.**
- 62 Examination of the bracket arm showed that the bracket foot assembly (figure 14) had parted at the point where the nylon insulator threads into the reducing sleeve, leaving both items damaged. The clevis cover and insulator remained attached to the pole bracket by the clevis pin, with the main body of the reducing sleeve remaining with the cantilever. The examination also found that the delta suspension connecting to the contact wire on the Wolverhampton line had been ripped from the clamp connecting it to the cantilever (figure 15) and that the register arm on this line was also disconnected. The Wolverhampton out-of-running pulleys had become separated from the cantilever at 18512 pole, although the out-of-running ropes and contact wires remained intact.
- 63 Of this damage, only the fracturing of the reducing sleeve could have caused the cantilever at 18512 pole to become partially detached without a tram being present, as was the case during this accident (paragraph 40). A failure of the contact wire delta and register arm would have caused the cantilever to detach only if it had resulted in the contact wire becoming entangled with a tram. However, the damage which these components sustained during the accident may indicate that a load was transferred through them into the cantilever at some point.

⁸ BS EN 50119:2009 'Railway applications. Fixed installations. Electric traction overhead contact lines'.



Figure 14: Damage to the bracket foot assembly of 18512 pole



Figure 15: Damage to the delta suspension of the Wolverhampton contact wire

The reducing sleeve failed due to an overload in the direction of Birmingham

- 64 The RAIB has been unable to fully determine how the failure of the reducing sleeve occurred. However, the mechanism by which it failed was due to it becoming overloaded in the along-track direction towards Birmingham.
- 65 Metallurgical examination indicated that the reducing sleeve failed in a brittle manner due to mechanical overload. There was no evidence of significant impact damage, fatigue or significant casting defects. Although there was evidence of superficial corrosion, this had not caused significant material loss.
- 66 The reducing sleeve was cracked around the thread run out of the smaller diameter thread (ie where it meets the insulator), with the crack extending approximately 180° around the thickness of the sleeve and then longitudinally through this thread (figure 16). This caused the detachment of segments on the Birmingham side, from approximately the 1 to 7 o'clock positions. These segments were distorted in the direction of Birmingham as they separated from the sleeve.

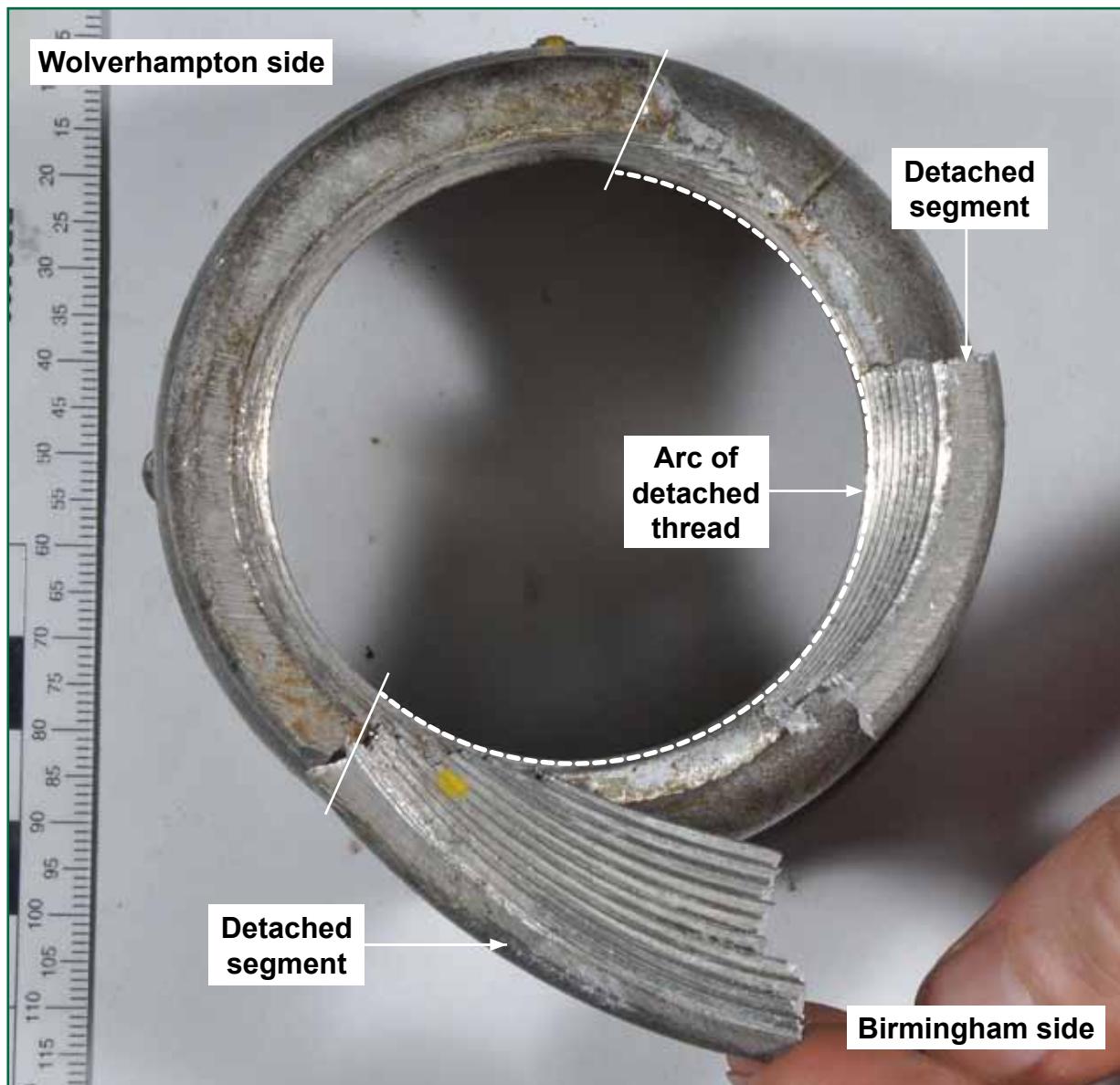


Figure 16: Damage to the reducing sleeve - two of the detached pieces of the smaller diameter thread have been re-positioned for photographic purposes

- 67 The nylon insulator was deformed in the direction of Birmingham and slightly upwards (figure 14). The thread at the reducing sleeve end of the insulator was damaged, with many threads being deformed or stripped on both sides. Taken together with the distortion of the reducing sleeve segments this clearly indicates that the overload force was applied in the direction of Birmingham.
- 68 There are two credible sources of this overload, namely;
- the way in which *operating loads* were able to act (the less likely cause - see paragraph 69); and
 - the introduction of an *abnormal load* following the parting of a Parafil rope (the most likely cause - see paragraph 103).

In both cases, the cantilever assembly needed to be restrained so that the load could act on the reducing sleeve and cause it to enter *yield* and fail. The RAIB has not been able to find conclusive evidence as to what created this restraint (paragraphs 102 and 119) and is therefore unable to fully determine how the failure of the reducing sleeve occurred.

Operating loads

- 69 **Operating loads within the OLE may have been able to act in a way which overloaded the reducing sleeve. However, the RAIB considers that this was less likely to have caused the accident than the introduction of an abnormal load.**
- 70 During normal operation, OLE systems are subject to operating loads (sometimes known as normal or permanent loads). These consist of the *self-weight load*, the *radial load* due to the forces in tensioned wires and ropes (both of which loads vary little in operation) and also the *variable loads*. Variable loads are imposed by factors such as ice or wind; given the weather conditions on 20 April 2011 they have been discounted as factors in the accident.
- 71 The operating load resulting from self-weight is that due to the weight of the bracket arm, contact wire, Parafil ropes and other equipment; it has both vertical and horizontal elements. The majority of the vertical element is borne by the tie ropes, which are in tension, with the entire horizontal load, which acts towards the pole, being carried in compression by the bracket foot assembly. The amount of self-weight load acting horizontally is dependent on the angle of the tie ropes, with shallower angles creating higher compressive loads in the bracket foot assembly and pole bracket.
- 72 Vertical load has been discounted as a cause of the overload of the reducing sleeve because of the direction of the overload (paragraph 67). Additionally, the vertical load was reduced in October 2010 by the removal of the feeder wires (paragraph 52) and there is no evidence that reducing sleeves failed as a result of these loads prior to this date.
- 73 The horizontal load at the bracket foot assembly at 18512 pole due to self-weight was determined by the RAIB to be approximately 14 kN. This would have been higher than at a non-overlap location because of the increased cantilever wall thickness and the additional weight of the overlap equipment (paragraph 34).

- 74 Where contact wires and their supporting ropes run at an angle to the centre line of the track (eg due to curves, stagger, or overlap arrangements) the tensile forces present in the contact wire produce an additional horizontal load, known as the radial load. Part of the operating loads, the radial loads always act towards the centre of curves and their magnitude is related to the contact wire tension, the span between poles and the radius of the curve. Most of the radial loads will be directed through the bracket foot assembly; however where the centre of the OLE pole is not exactly aligned with the centre of the curve (as in the case of 18512 pole) a relatively small amount of radial load will also act in the along-track direction.
- 75 The total radial load applying towards the bracket foot assembly was determined by the RAIB to be approximately 8 kN when the bracket arm was perpendicular to the centre line of the track. Part of this load was due to the contact wires passing around the curve. However the majority of it resulted from the out-of-running Parafil ropes, which passed over pulleys attached to the cantilever, prior to diverging at a relatively sharp angle to their anchor points. Adding this to the load due to self-weight, the total compressive load through a cantilever installed perpendicular to the track would have been approximately 22 kN. Analysis undertaken by the RAIB has determined that the components of the bracket foot assembly (including the reducing sleeve) could safely withstand this load.
- 76 The distortion of the reducing sleeve segments and the deformation of the nylon insulator indicate that the cantilever was deflected towards Birmingham prior to the sleeve failing. Measuring the angle of deformation of the insulator (some of which may have been caused as a result of the dewirement) and extrapolating it over the typical cantilever length (7.97 metres) indicates that the end of the cantilever at 18512 pole was deflected by no more than approximately 550 mm from its position when perpendicular to the centre line of the track.
- 77 The RAIB used *Finite Element Analysis* and other analytical methods to examine the effect of operating loads when the cantilever was deflected from a position perpendicular to the centre line of the track. This analysis assumed a deflection of the cantilever end of 800 mm, which is larger than the probable maximum deflection seen during the accident and greatly beyond the expected movement of the cantilever in normal service. This analysis concluded that the bracket foot assembly could safely withstand the operating loads present when deflected to this extent, provided it was able to freely rotate around the pole bracket pin and the cantilever was otherwise unrestrained.
- 78 Further analysis of the effects of the operating loads found that they would only introduce a bending moment sufficient to cause the reducing sleeve to enter yield if:
- the bracket foot assembly became restrained from rotating around the pole bracket pin and the cantilever end was deflected by 400 mm (figure 17); or
 - the cantilever became fixed at some point along its length such that a cantilever deflection could apply a bending moment on the reducing sleeve. For example, if the Birmingham contact wire delta was able to act as a pinned joint, then deflecting the cantilever end by 400 mm would also result in the reducing sleeve entering yield (figure 18).

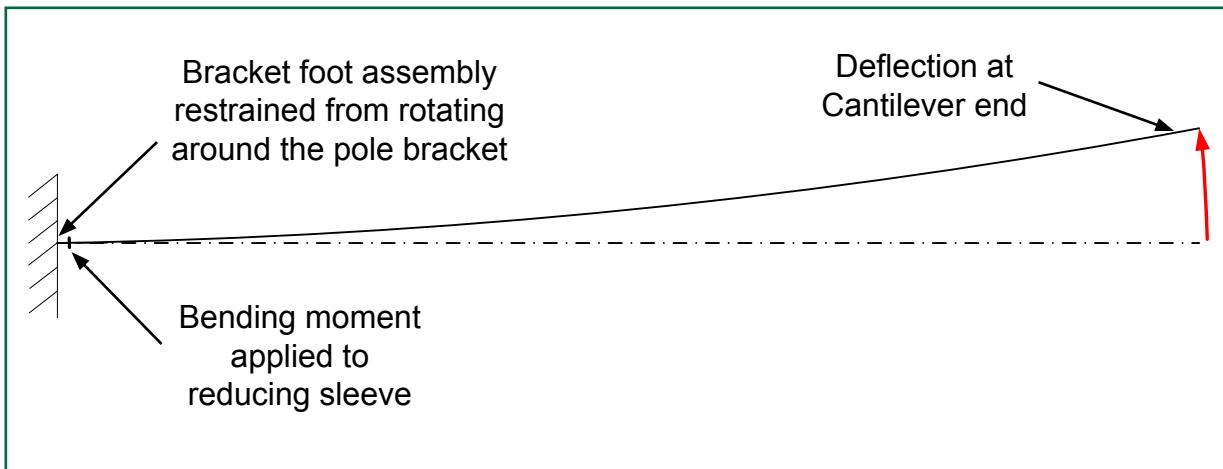


Figure 17: Diagrammatic representation of the bracket foot assembly becoming restrained from rotating around the pole bracket and the cantilever end being deflected

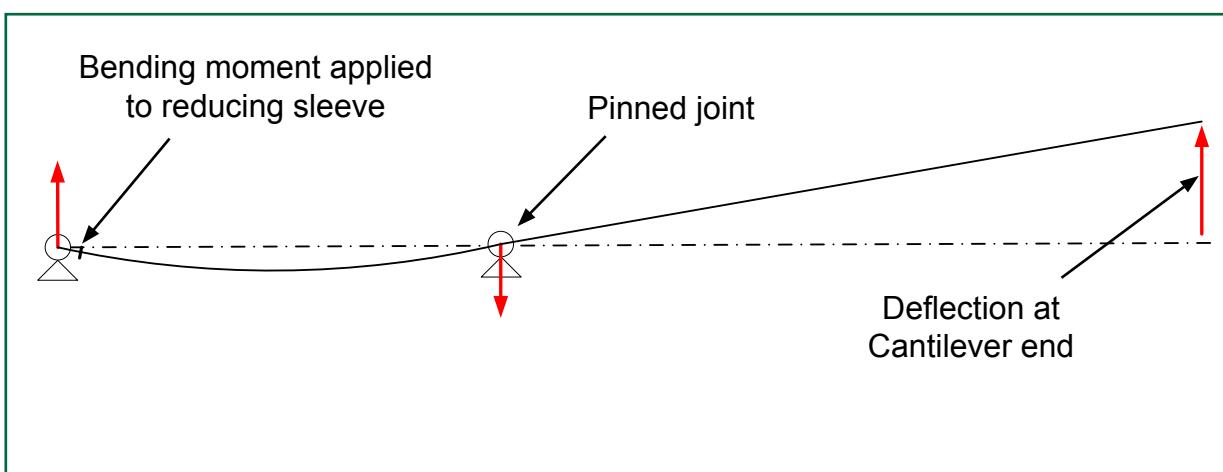


Figure 18: Diagrammatic representation of the cantilever becoming fixed at some point along its length and the cantilever end being deflected

Causes of cantilever deflection

- 79 The cantilever at 18512 pole may have been deflected from a position perpendicular to the centre line of the track due to a number of factors including contact wire expansion with temperature change, the initial set-up of the cantilever and *metallurgical creep* of the contact wire. This latter factor is most significant in the early days of operation of a network and given that creep was removed from the Midland Metro's contact wires between 2005 and 2006, it has been discounted as a possible cause of the accident.
- 80 Contact wires are subject to the heating effect of the sun, to variations in the surrounding ambient temperature and to heat resulting from electrical current being drawn by the trams. Changes in the temperature of the contact wire result in its expansion and contraction. The OLE system accommodates these changes of length by clamping the delta of the outer contact wire to the cantilever whilst the delta of the inner contact wire can pass freely over a pulley. This means that at 18512 pole the movement of the Wolverhampton contact wire drove the deflection of the cantilever.

- 81 At 18512 pole, any change in contact wire length due to the varying thermal effect of ambient temperature, solar heating and electrical current is minimised because this pole is located close to an anchor point. Because of this, it would require a change in the temperature of the contact wire of over 150 °C (well beyond that expected in normal operation) for this to equate to the 400 mm cantilever end deflection needed for the reducing sleeve to yield (paragraph 78). The effect of a change in contact wire temperature alone could therefore not have generated sufficient deflection of the cantilever to cause the sleeve to yield, although a smaller change in temperature may have contributed to a larger overall deflection.
- 82 The installation manual for the OLE system states that cantilevers situated at poles less than 360 m from an anchor point (such as 18512 pole) should be installed so that they are perpendicular to the centre line of the track. However, the length of the cantilever means that only a relatively small angle from the perpendicular is needed to create a significant deflection at the cantilever end (eg 3° equates to an end deflection of 400 mm). This means that it is difficult to align the cantilever, either from the ground or from elevated work platforms, so that it is in the perpendicular position. It is credible therefore that the installation of the cantilever could have introduced sufficient deflection of the cantilever, either alone or in combination with other factors, for operating loads to cause the reducing sleeve to enter yield, provided the conditions discussed in paragraph 78 were satisfied.
- 83 In August 2009, 18512 pole underwent significant repair work following a dewirement (paragraph 51). During this work VolkerRail Power removed and re-fitted the cantilever, working to the verbal instructions of NXMM staff. This was the last opportunity before the accident for a deflection to be introduced during installation of the cantilever. Once the work was completed, the repaired OLE was inspected and accepted back into service by NXMM staff.
- 84 VolkerRail Power were provided with a set of documentation relating to the tramway at the start of their contract with NXMM. This consisted of call-out procedures, line diagrams, safe work practices and the 'as-built' wire-height and stagers for the network. VolkerRail Power stated that they requested access to design information to provide under-pinning knowledge for their repairs, but that this was not made available to them. This meant that they felt reliant on the technical knowledge and instructions of NXMM staff when undertaking repairs.
- 85 When re-installing cantilevers, VolkerRail Power stated that their staff would try to match the position and orientation of a modified pole bracket (paragraph 35) to the one which had been removed and that they would fit new tie ropes so they connected at the same point along the length of the cantilever. There was no particular instruction from NXMM regarding the degree of cantilever deflection required nor did they have access to the installation manual. This lack of available information regarding the set-up of the cantilever was a potential underlying factor in the accident.
- 86 Further work was carried out on 18512 pole in October 2010 (paragraph 52). It is possible that this modification work may also have affected the degree of deflection of the cantilever. As part of the programme of activities undertaken at this time, the parallel feeder cables were remounted on the OLE poles (figure 7) in order to reduce the self weight of the OLE.

- 87 The parallel feeders were originally clamped to the cantilevers and had a fixed tension of between 3 and 10 kN dependent on temperature. This tension would have acted to restrain the movement of the cantilever and may have restricted the degree of deflection towards Birmingham. Therefore it is possible that remounting the parallel feeders wires onto the OLE poles, although not introducing any additional deflection, may have removed a restraint which had previously acted to limit deflections created by other causes. The period covering 19 and 20 April 2011 was only the second time since the feeder wires had been moved that the ambient temperature in Birmingham had reached 21 °C. It is possible, therefore, that the cantilever could have deflected more on these days than at any other time since October 2010.
- 88 The potential for the removal and remounting of the parallel feeder wires to result in a loss of restraint in the movement of the cantilever was not appreciated when the technical specification for the October 2010 modification programme was created by Brecknell Willis or when the modification programme was examined as part of NXMM's *safety validation* process. This was also potentially an underlying factor in the accident.

Restraint of the bracket foot assembly

- 89 The pole bracket fitted to 18512 pole at the time of the accident was of the modified design (paragraph 35), made of steel and with a rounded clevis (figure 19). This design had a longer clevis than the original design (figure 20) and so could contact the clevis cover of the bracket foot assembly when the two items were pressed together under the action of the operating loads.



Figure 19: An example of a modified design of pole bracket



Figure 20: An example of an original design of pole bracket

- 90 Post-incident inspection showed evidence of contact between the bracket clevis and the clevis cover of the bracket foot assembly recovered from 18512 pole. The bracket clevis had either a rough or damaged face (figure 21) whilst the clevis cover showed both wear marks and evidence of rust (figure 22). This rust could only have resulted from contact with a steel item, such as the pole bracket (the clevis cover is made from aluminium bronze and would not produce rust).

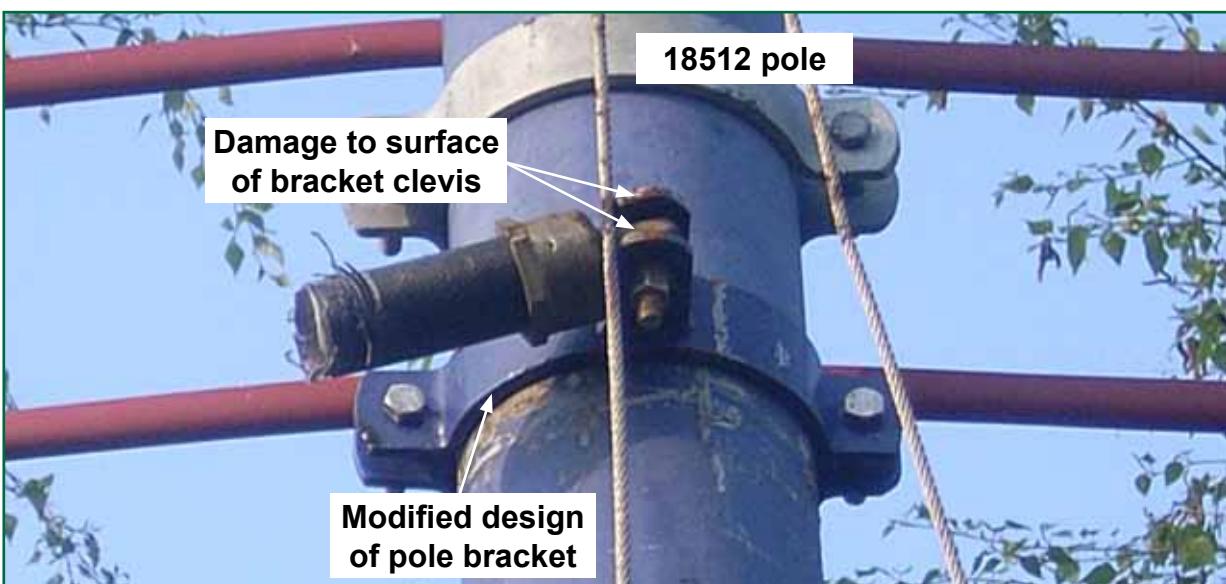


Figure 21: Modified design of pole bracket in-situ at 18512 pole following the accident

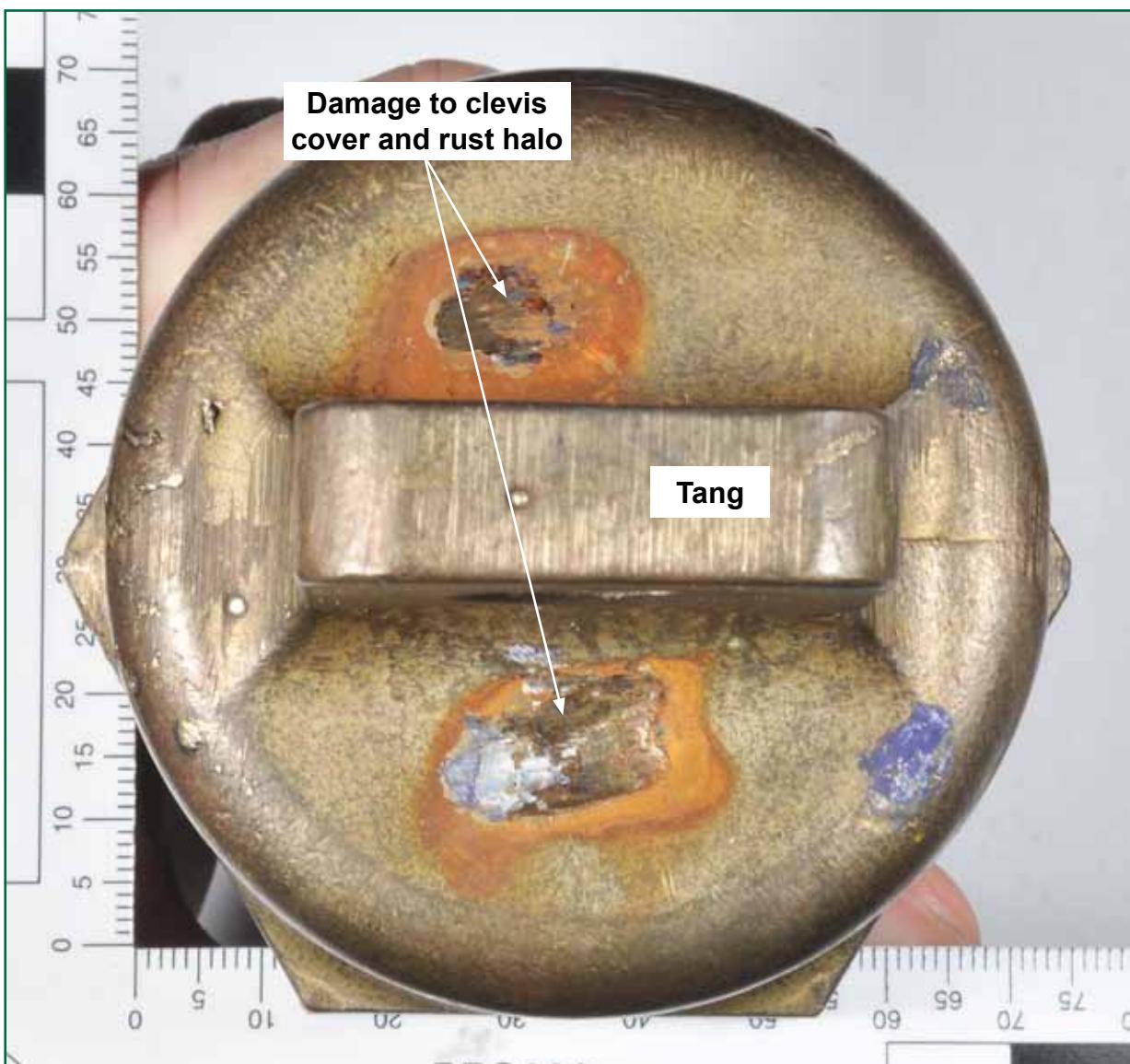


Figure 22: Marks on the clevis cover of the bracket foot assembly taken from 18512 pole

- 91 It is also of note that, during recovery operations following the accident, there was a comparable failure of a reducing sleeve on another pole whilst the contact wires were being connected. In this second failure, the bracket foot was unable to rotate because it had been fitted in error to a tie rope pole bracket (figure 23) which had a square-faced profile.
- 92 Despite there being evidence of contact between the bracket clevis and clevis cover at 18512 pole, analysis showed that, whilst this may have caused some restriction of movement, the friction created would have been insufficient to react the magnitude of bending moment required to yield the reducing sleeve ie the clevis cover would slip across the face of the bracket clevis before the reducing sleeve started to yield.

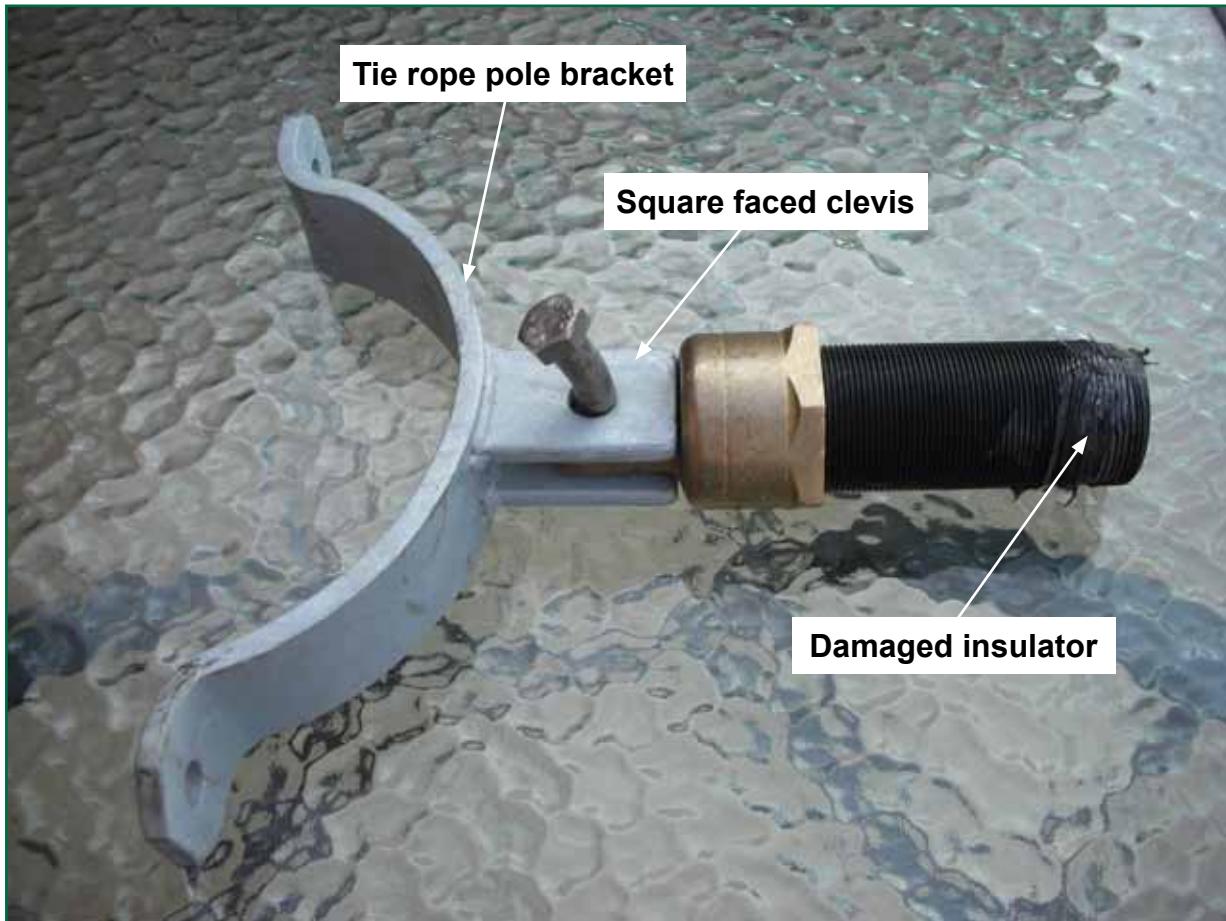


Figure 23: Bracket foot assembly which failed post incident, connected to a tie rope pole bracket featuring a square faced clevis (image courtesy of National Express Midland Metro)

- 93 Testing and analysis indicated that the presence of a small flat profile of 10 mm on the bracket clevis would react the bending moment necessary to yield the reducing sleeve through the clevis pin and the tang of the clevis cover. However, this reaction load would also be expected to distort the tang of the clevis and/or the clevis pin (in a similar manner to that shown in figure 23). Although the clevis pin fitted at the time of the accident was not available for examination by the RAIB, the inspection of the tang of the clevis cover showed no obvious evidence of such distortion, nor was there any evidence of a flat being present on the bracket clevis.
- 94 Neither the post-incident survey of the OLE, nor metallurgical examination of the bracket foot assembly, found any evidence of damage which might indicate that an item had become trapped between the bracket and clevis cover in a way that could have prevented the bracket foot from freely rotating. Had an item become trapped in this way, it would have again caused distortion to the clevis pin and/or to the tang of the clevis cover when reacting a bending moment sufficient to fail the reducing sleeve (see figure 17).

- 95 Although there is evidence of contact at the clevis cover which may have created some restriction of movement, this on its own probably could not have restrained the bracket foot assembly sufficiently to cause the reducing sleeve to fail. The RAIB considers therefore that the bracket foot assembly becoming restrained was on its own not likely to have been a causal factor to the accident. However it is possible that some degree of restriction at this position could have acted in combination with another source of restraint along the length of the cantilever and so contributed to the failure.

Restraint along the length of the cantilever

- 96 The cantilever could have become restrained at a point along its length, thus creating a pivot, due to the way in which the out-of-running pulleys or the contact wire delta suspension for the Birmingham line behaved when subjected to static and/or dynamic loads. Post-incident inspection showed that the Wolverhampton out-of running pulleys had become separated from 18512 pole; however both they and the Wolverhampton contact wire were discounted as likely pivots due to their relative proximity to the end of the cantilever.
- 97 The out-of-running pulleys on 18512 pole are machined from solid nylon. They rotate around a stainless steel shaft onto which they are mounted via plain 'Railko' bearings. The inner⁹ of the two pulleys is clamped by metal banding to the cantilever via a box shaped mounting. The outer of the two pulleys is fixed to this inner pulley by a metal plate, through which both mounting bolts pass. The outer pulley is then connected to the cantilever by a 'quick link' shackle and another bracket (figure 11).
- 98 The design and materials used for the out-of-running pulleys should allow them to rotate and for the steel portion of the out-of-running rope to pass freely. There have been no reported examples of the plain 'Railko' bearings seizing on the Midland Metro or other networks. There was also no evidence of the connectors which join the Parafil and steel portions of the out-of-running ropes having jammed in the pulleys or of any other relevant damage which could suggest how they could have restrained the cantilever.
- 99 There was anecdotal evidence that in and out-of-running ropes had previously applied a torque to the cantilever and that the high radial loads generated by the out-of-running ropes may sometimes cause pulleys to lock. However, analysis undertaken by the RAIB has shown that, even were a pulley to become locked in this way, the friction generated between the steel rope and nylon pulley sheave would have been below that needed to restrain the cantilever so that a load could be reacted into the bracket foot assembly that was sufficient to cause the reducing sleeve to fail.
- 100 Contact wire deltas take the form of a 7 mm diameter Parafil bridle (paragraph 24). At the apex of the bridle, the Parafil is held either within a metal clamp (Wolverhampton line) through which it cannot slide or runs freely over a small plastic pulley (Birmingham line). Both are suspended from brackets on the cantilever using a combination of shackles and/or quick links. This gives the pulleys or clamps the ability to accommodate limited movement within the registration of the contact wire.

⁹ The pulley closest to the OLE pole.

- 101 There was no evidence to suggest that the Birmingham contact wire delta had become damaged or jammed in anyway which would allow it to restrain the cantilever and react a load into the bracket foot assembly.
- 102 In summary, there is no direct evidence that the out-of-running ropes or contact wire delta suspension on the Birmingham line restrained the cantilever and thus created the pivot mechanism which would have caused the sleeve to fail. However, a post-incident inspection of 18512 pole in July 2011 showed that the insulator (which was fitted after the April 2011 accident) had already deformed and was not at the same angle as the rest of the bracket arm assembly (figure 24). During this inspection a pole bracket type with a different and flatter profile of clevis was fitted, compared with that in place on 20 April 2011. This deformation does, nevertheless, provide evidence that operating loads within the OLE can apply a bending moment to the bracket foot assembly at this location.

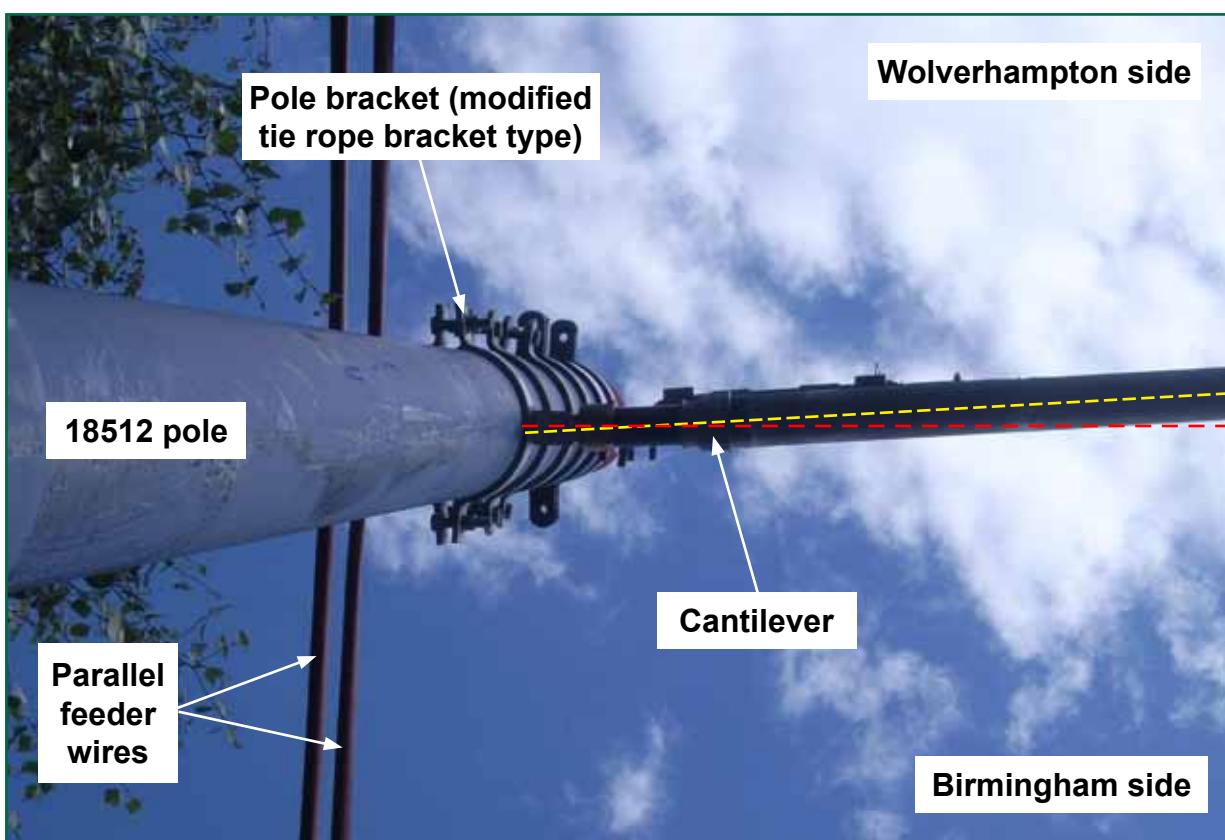


Figure 24: Photograph of 18512 pole taken in July 2011 showing insulator deformation

Abnormal loads

- 103 An abnormal load could have been introduced into the OLE system. This was more likely to have been the cause of the accident than the action of operating loads.
- 104 Within an OLE system an abnormal load is created when a component fails which results in the release of tension (this is also known as an accidental load). On the Midland Metro, such a load could be introduced by the failure of a contact wire, of an in/out-of-running rope or of the connectors and terminations which join these wires and ropes to each other and to anchor points and gas tensioners.

- 105 Following the accident, the outer¹⁰ of the two Wolverhampton in-running Parafil ropes was found to have parted at a point around mid-way along its length, consistent with where it passed over the cantilever at 18432 pole. This rope had been connected to an anchor point at 18392 pole before passing over the cantilever at 18432 pole and connecting to the steel wire rope which ran through one of the in-running pulleys at 18472 pole. On leaving the pulley, the rope would ultimately connect with the outer of the two contact wires on the Wolverhampton line before it descended towards running height and joined with the inner wire (figure 7, 8 and 9). This twin contact wire was held by a delta suspension which was clamped to the cantilever at 18512 pole (figure 15).
- 106 A failure of the outer of the two Wolverhampton in-running Parafil ropes would have applied a brief transient load to the cantilever of 18512 pole via the contact wire delta suspension and its clamped connection to the cantilever, prior to the gas tensioner and the remaining intact in-running Parafil rope returning the system to equilibrium. The damage to the Wolverhampton line delta bridle and register arm noted post incident may be indicative of the transfer of a load through these components and into the cantilever (paragraph 62).
- 107 The in/out-of-running ropes were made from a type F Parafil rope. This consists of a core of high-strength parallel aramid fibres, enclosed within a polyethylene sheath. Both Brecknell Willis and the manufacturer of the Parafil rope used on the Midland Metro had previously only experienced Parafil failing in service due to water ingress at connectors and terminations. This results in a chemical process known as *hydrolysis*, which can break down aramid fibres and reduce their strength. Aramid fibres are also adversely affected by prolonged exposure to ultra-violet (UV) light. The aramid core of Parafil rope is protected from the effects of both water and ultra-violet light by the sheath and by the use of specialist sealed connectors and terminations.
- 108 Although the fibres within Parafil rope are strong under tension, they do not have a high resistance to abrasion. For some types of Parafil rope, the sheath may provide protection from abrasion, although this is not the case with type F Parafil. There is instead general guidance from Brecknell Willis that a mechanical clearance of 80 mm¹¹ be maintained between this Parafil rope type and any item which could damage it, although this clearance can be reduced at the discretion of the installer¹².
- 109 The outer of the two Wolverhampton in-running Parafil ropes was not seized by the RAIB as evidence, as it was initially thought to have failed as a consequence of the dewirement. However, photographs taken of the rope end where it parted do not show any obvious signs of either hydrolysis or of degradation caused by prolonged exposure to UV light. The photographs show that the exposed aramid fibres were mostly short with a smaller number of longer strands, characteristic of a tensile failure in a Parafil rope. The condition of the parted end of the rope is consistent with most of the fibres being cut or abraded prior to a failure of the remaining intact part of the rope in tension due to overload.

¹⁰ The in-running contact wire assembly furthest from the OLE pole.

¹¹ Live OLE components may also need to observe an electrical clearance from other components to ensure that sufficient electrical insulation is provided by the air between them.

¹² Because of their low mass and high tension, Parafil ropes at overlaps are only minimally affected by deflection due to the variable force of wind (normally referred to as "blow-off").

110 The damage to this rope could have occurred either prior to the accident or as part of the collapse of the OLE which followed it, although it is significant that the Parafil seems to have parted where it ran in close proximity to the tie ropes supporting the cantilever at 18432 pole. The evidence available to the RAIB is that the parted tie rope ran between the inner-most and middle tie ropes, although it is inconclusive as to whether the Parafil rope was able to touch these tie ropes prior to April 2011. However a post-incident inspection of 18432 pole in July 2011 showed that the inner of the two Wolverhampton in-running Parafil ropes was touching the inner-most steel tie rope as it passed over the cantilever (figure 25).

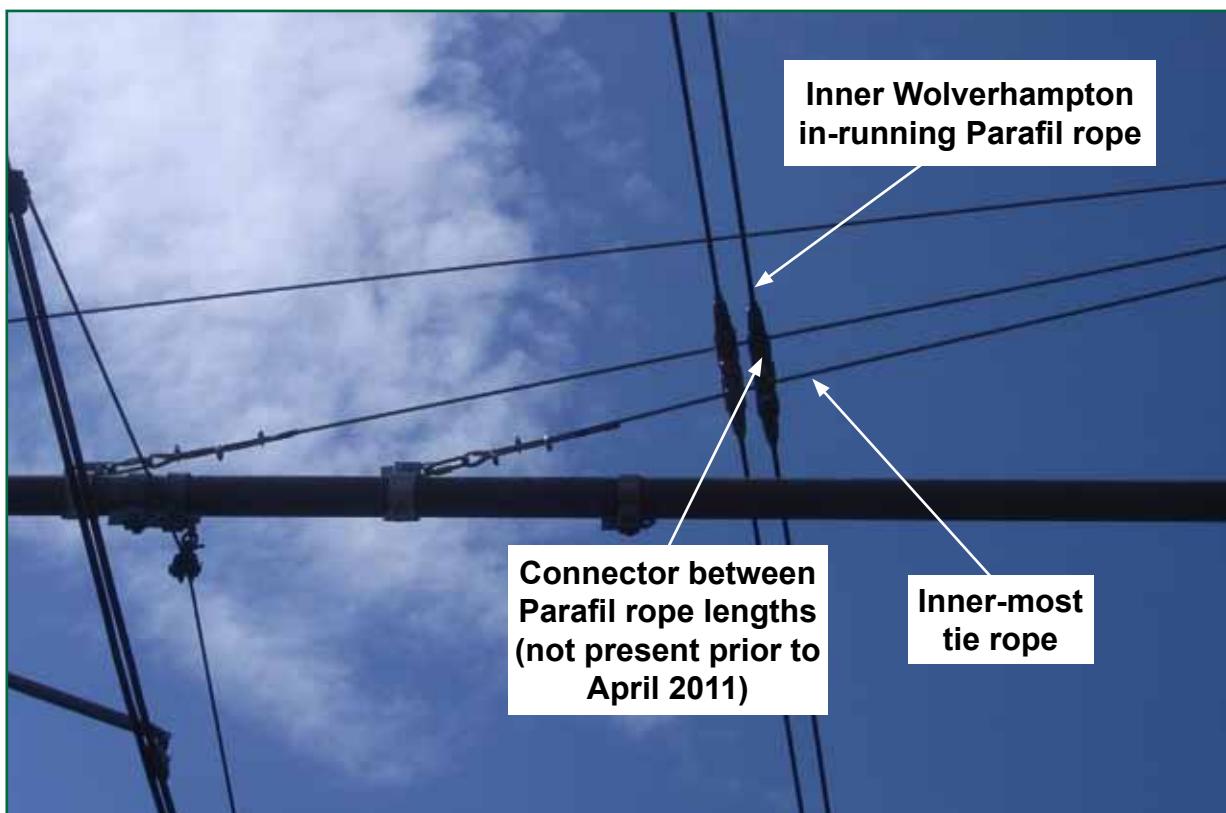


Figure 25: Inner Wolverhampton in-running Parafil rope touching a tie rope at 18432 pole – photograph taken in July 2011

111 After the accident the in-running Parafil ropes were replaced using lengths of Parafil joined by a sealed connection. It was this connection, which was not present prior to April 2011, that was found to be touching a tie rope in July 2011. The configuration of tie ropes at this pole had also been changed following the accident and therefore the July 2011 inspection does not provide conclusive proof that there was contact between tie ropes and Parafil ropes prior to April 2011. However, it does provide supporting evidence that the geometry of the OLE at this location can result in reduced mechanical clearances.

112 A reduced mechanical clearance could have been introduced either;

- during dewirement repairs in August 2009, when the previous configuration of two Parafil tie ropes was replaced with three tie ropes (paragraph 28); or
- during the October 2010 modification programme, when the three steel tie ropes fitted in August 2009 were replaced by three steel tie ropes of a different design (paragraph 28).

- 113 Staff working for Keltbray Aspire who undertook the October 2010 modification programme used an elevated work platform and worked in close proximity to the tie ropes and Parafil in-running ropes. Witness evidence was that a reduced mechanical clearance or existing damage to a Parafil rope (which would have been conspicuous due to the light-colour of the inner fibres becoming exposed) would have been noted and addressed as part of the modifications work. As witness evidence also stated that neither was present, it seems more likely that a reduced mechanical clearance was introduced as a result of, and not prior to, these modifications.
- 114 NXMM assessed the risks associated with the October 2010 modifications as part of their safety validation process. Risk mitigation identified included the inspection of the modified OLE prior to its acceptance back into service by a representative from Brecknell Willis, who had written the original technical specification. This person would also attend the works at their start and mid-point to help resolve technical queries.
- 115 Once the modifications were finished at a particular location, Keltbray Aspire examined the work and recorded what had been done (these work records were lost and therefore have not been reviewed by the RAIB) prior to the overall inspection of the completed works by Brecknell Willis. This inspection was undertaken during daylight hours on 31 October, using an elevated work platform. Witness evidence is that the inspection showed that significant work remained to be completed before the system could be tested and accepted back into service for the following day. The RAIB has concluded that, given the time available and the volume of work outstanding, there was probably pressure on the staff involved to quickly finish the work. Work completed after the inspection was not re-examined by Brecknell Willis due to time constraints and the loss of daylight.
- 116 It is not possible to say definitively if a reduced mechanical clearance between the tie ropes and the in-running tension length at pole 18432 could have been missed due to incomplete inspection or introduced during work being completed under time pressure. However both are potentially underlying factors to the accident.
- 117 Regular OLE inspections undertaken by NXMM following the modification in October 2010 did not detect any loss of mechanical clearance at 18432 pole. Although the track walk conducted with the RAIB in July 2011 (paragraph 111) successfully identified a reduced mechanical clearance at this location, it was clear that these can be difficult to spot, particularly if the inspection is conducted on foot. It is possible therefore that a routine inspection of the OLE could miss a reduced mechanical clearance. This is also a possible underlying factor to the accident.
- 118 The RAIB undertook Finite Element Analysis of the transient abnormal loads which could be created by the failure of the outer Wolverhampton in-running Parafil rope. This demonstrated that a load of this nature could cause the reducing sleeve to fail if:
- the bracket foot was restrained from rotating around the pole bracket pin; and/or
 - the cantilever became fixed at some point along its length, creating a pivot.

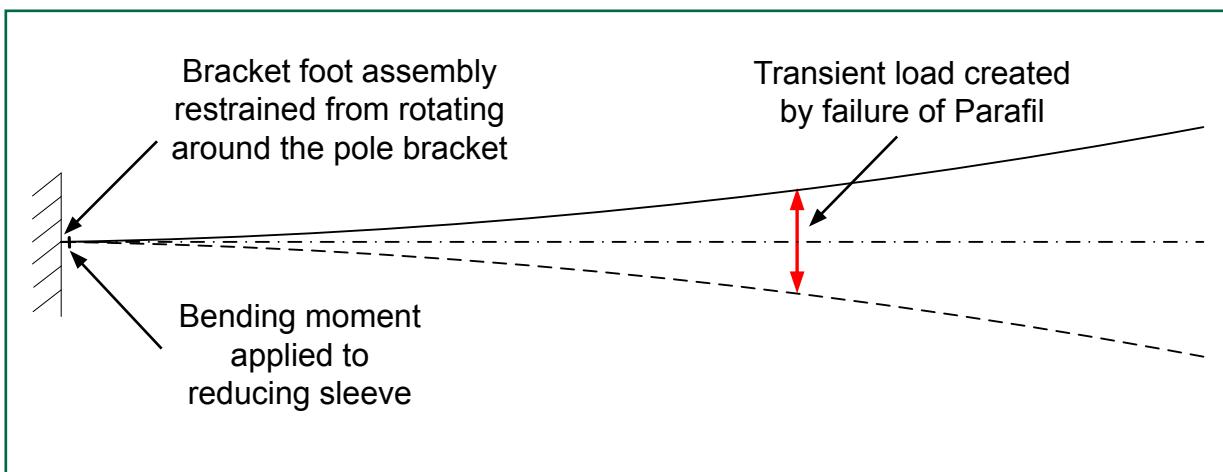


Figure 26: Diagrammatic representation of the bracket foot being restrained from rotating around the pole bracket pin and a transient load was created by the failure of the Parafil

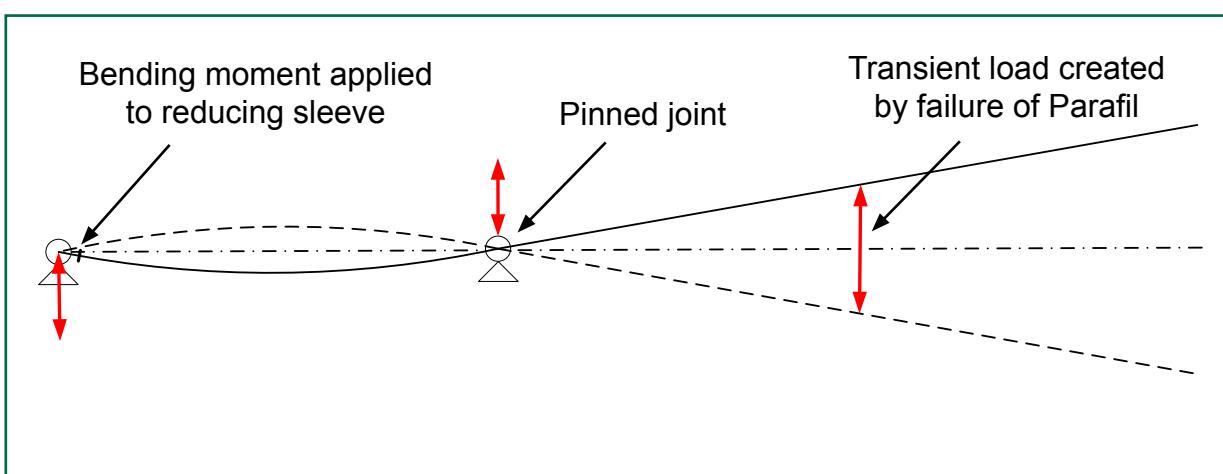


Figure 27: Diagrammatic representation of the cantilever becoming fixed at some point along its length and a transient load being created by the failure of the Parafil

- 119 As explained in paragraph 95, the bracket foot assembly probably could not, on its own, have reacted the bending moment necessary to cause the sleeve to yield, although it was possible that a restriction at this location could have acted in combination with a source of restraint along the length of the cantilever and so contributed to the failure. However, there was no evidence as to how the cantilever could have been restrained along its length so as to create a pivot (paragraph 102).
- 120 It is, however, possible that a momentary restraint was created around the out-of running pulleys and/or the contact wire delta suspension for the Birmingham line due to the reaction of the system to a large transient force (eg the effects of inertia, the stiffness of the bracket arm and friction). This reaction may have temporarily created a pivot which could, either on its own or possibly in combination with a degree of restriction at the bracket foot, have created a bending moment sufficient to cause the reducing sleeve to fail. The application of a large transient force in this manner would be more typical of abnormal loads than of operating loads, which change gradually. With this in mind, the RAIB considers that the introduction of an abnormal load due to failure of the outer Wolverhampton in-running Parafil rope was therefore the most likely cause of the failure of the reducing sleeve and the partial detachment of the cantilever at 18512 pole.

Consequences

Passenger injury mechanism

121 The injuries sustained by the passengers during the accident were the result of flying glass entering the tram after the saloon windows, saloon door glass panels and the right-hand-side driving cab partition screen were struck by cantilevers which had become detached from the OLE during its progressive collapse and dewirement. The density of flying glass was highest within the leading right-hand side of the passenger saloon which is also where the majority of the injuries occurred.

Observations¹³

Supply chain control

122 Reducing sleeves cast from malleable iron were tested by Brecknell Willis during the design of the OLE. The casting material was subsequently changed to aluminium bronze by the reducing sleeve manufacturer in 1997 and it was this type of sleeve that was fitted to bracket arms during the original construction of the network. The casting material was changed a second time by the sleeve's manufacturer in 2007 to aluminium alloy; it was a sleeve of this type supplied by Brecknell Willis which was fitted to the bracket arm of 18512 pole at the time of the accident. The date of manufacture of this reducing sleeve shows that it was installed as a replacement during the August 2009 dewirement repairs (paragraph 51).

123 It became apparent during the investigation that neither NXMM nor Brecknell Willis were aware of the 2007 change in casting material. Testing undertaken by Brecknell Willis following the accident indicates that reducing sleeves cast from aluminium alloy perform no worse than those cast from malleable iron when subjected to bending moments. For this reason, the RAIB considers that the lack of awareness of the change in material from that tested during design was not causal to the accident. It is, however, undesirable for there to have been a change in a component of this nature and for neither the supplier of the component nor the tramway operator to have been aware of it.

Staff training and equipment

124 The CSR had received no training which would have enabled him to have managed an emergency evacuation of the tram, or an OLE incident, or to have acted as PRIMOS (paragraph 21). As he was not equipped with a cab key he would also have been unable to have gained access to the driving cabs, had he needed to do so. As the driver was not incapacitated following the accident and because the damaged OLE equipment was clear of the passengers as they exited onto the platform, none of this placed either staff or passengers at any increased risk of injury on 20 April 2011.

¹³ An element discovered as part of the investigation that did not have a direct or indirect effect on the outcome of the accident but does deserve scrutiny.

- 125 Nevertheless, a driver could potentially become incapacitated within a wide range of possible scenarios¹⁴. In this event it is likely that, as the sole remaining member of NXMM staff onboard, the CSR may need (amongst other tasks) to have radio contact with Metro Control, to access the driving cabs and to manage an evacuation of the passengers.
- 126 Witness evidence has indicated that the workload of training staff within the Midland Metro has led to drivers and CSRs being unable to complete their scheduled professional development days. One of these days is rostered for each driver and CSR every 42 weeks and is intended to allow staff to renew any expiring mandatory competences and to complete other optional development training. Should a day be missed for any reason, then it will be 42 weeks until the next opportunity arises; this has meant that some drivers and CSRs, having missed their particular day, have subsequently been required to continue working whilst holding mandatory competences which have expired.

¹⁴ Possible incapacity of staff on a tram following an incident was identified by NXMM during risk assessment in 2009; however possible incapacity of the driver alone was not considered in this assessment.

Summary of conclusions

Immediate cause

127 The immediate cause of the accident was the collapse of the overhead line caused by Tram 13 striking the partially detached cantilever at 18512 OLE pole (**paragraph 53**).

Causal factors

128 The cantilever became partially detached because the reducing sleeve was overloaded and fractured. This overloading was a consequence of:

- a. the cantilever becoming momentarily restrained at some point along its length, thus creating a pivot (**paragraph 120, no recommendation**); and either
- b. the introduction of an abnormal load resulting from the severing of the outer of the two Wolverhampton in-running Parafil ropes (the most likely causal factor) (**paragraph 103, Recommendation 1**); or
- c. the action of operating loads within the OLE (the less likely causal factor) (**paragraphs 69 and 102, Recommendation 3**).

129 Possible factors were:

- a. the bracket foot assembly becoming restrained to some degree from rotating around the pole bracket pin and thereby contributing to the restraint of the cantilever (**paragraphs 89 and 95, Recommendations 4 and 5**);
- b. the expansion of the contact wire due to ambient temperature (**paragraphs 81 and 87, no recommendation**);
- c. the deflection of the cantilever during installation or modification so that it was not perpendicular to the centre line of the track (**paragraphs 82 and 86, Recommendation 3**); and
- d. a reduced mechanical clearance between the tie ropes at 18432 pole and the Wolverhampton in-running Parafil ropes (**paragraph 112 , Recommendation 1**).

Underlying factors

130 Possible underlying factors were:

- a. the lack of information available to VolkerRail Power staff regarding the correct installation of cantilevers (**paragraph 85, Recommendation 2**);
- b. during safety validation of the proposed OLE modification programme, the potential for the remounting of the parallel feeder wires to result in a loss of restraint of the cantilever was not considered (**paragraph 88, no recommendation**);

- c. due to work being completed under time pressure and owing to an incomplete inspection, a reduced mechanical clearance was introduced at pole 18432 and then not discovered before the network was returned to service (**paragraph 117, Recommendation 1**); and
- d. the regular OLE inspections undertaken by NXMM following the modification in October 2010 were not able to detect a potential loss of mechanical clearance at 18432 pole (**paragraph 117, Recommendation 1**).

Additional observations

131 Although not causal to the accident on 20 April 2011, the RAIB observes that:

- a. the material used to make reducing sleeves (including those in place at 18512 pole) had been changed without either Brecknell Willis or NXMM being aware that this had happened (**paragraph 123, Recommendation 5**);
- b. the CSR received no training which would have enabled him to have initiated an emergency evacuation of the tram or to deal with the incident had the driver been incapacitated (**paragraph 125, Recommendation 6**);
- c. as the CSR was not equipped with a cab key he was unable to access the leading cab to check on the condition of the driver without going outside of the tram (**paragraphs 124 and 132, no recommendation**); and
- d. the workload of training staff within the Midland Metro has led to drivers and CSRs being unable to complete their scheduled professional development days. This has meant that some drivers and CSRs have subsequently been required to continue working whilst holding mandatory competences which have expired (**paragraph 126, Recommendation 7**).

Actions reported as already taken or in progress relevant to this report

Actions reported that address factors which otherwise would have resulted in a RAIB recommendation

132 CSRs on the Midland Metro have now been issued with a cab key. Although this is primarily intended to allow them access to the trailing cabs of trams in service in order to obtain spare ticket rolls, it could also be used in an emergency to gain access to the leading cab and driver from the saloon.

Other reported actions

133 Immediately after the accident, NXMM put in place a Temporary Speed Restriction (TSR) which limits trams to a maximum permitted speed of 40 km/h between the All Saints road bridge (around 260 metres before 18512 pole) and the Jewellery Quarter tram stop. This is intended to give tram drivers more reaction time should a further OLE failure occur and to mitigate the effect of a collision between a tram and anything which may foul its passage as a result of such a failure.

Recommendations

134 The following recommendations are made¹⁵:

- 1 *The purpose of this recommendation is to prevent damage to tensioned components within the Midland Metro OLE system which may result in their failure.*

National Express Midland Metro should determine the minimum mechanical clearance necessary around tensioned components within the OLE system to prevent contact that may damage them. It should introduce controls to prevent smaller clearances than this minimum from either being introduced into the system or developing during operational service and not being detected (paragraphs 128b, 129d, 130c and 130d).

- 2 *The purpose of this recommendation is to ensure that persons holding responsibility for directing work on the OLE on the Midland Metro and/or for passing it as being fit for service have access to up-to-date and relevant information regarding its correct installation and configuration.*

National Express Midland Metro should ensure that staff within its organisation that hold responsibility for supervising work on the OLE and/or for passing it as being fit for service have access to the information needed for them to confirm its correct installation and configuration. This information should be up-to-date and accurate and would typically include items such as manuals, drawings or other supporting documents. This information should be made available to any third-parties undertaking similar duties (paragraph 130a).

continued

¹⁵ Those identified in the recommendations, have a general and ongoing obligation to comply with health and safety legislation and need to take these recommendations into account in ensuring the safety of their employees and others.

Additionally, for the purposes of regulation 12(1) of the Railways (Accident Investigation and Reporting) Regulations 2005, these recommendations are addressed to The Office of Rail Regulation to enable it to carry out its duties under regulation 12(2) to:

- (a) ensure that recommendations are duly considered and where appropriate acted upon; and
- (b) report back to RAIB details of any implementation measures, or the reasons why no implementation measures are being taken.

Copies of both the regulations and the accompanying guidance notes (paragraphs 200 to 203) can be found on RAIB's web site www.raib.gov.uk.

- 3 *The purpose of this recommendation is to ensure that the mechanism(s) by which operating loads are able to deform the twin track bracket arm assembly at 18512 pole are identified and addressed.*

National Express Midland Metro should determine how the operating loads within the OLE are able to cause the type of deformation observed in the twin track bracket arm assembly at 18512 pole in July 2011. It should identify and implement appropriate measures to remove the causes of this deformation (paragraphs 128c and 129c).

- 4 *The purpose of this recommendation is to ensure that the ability of bracket foot assemblies to rotate freely is not restricted by contact between pole bracket clevises and clevis covers.*

National Express Midland Metro should inspect the tensioned section of the OLE to ensure that there is clearance between the clevises of OLE pole brackets and the clevis covers of bracket foot assemblies sufficient to allow these assemblies to rotate freely around pole bracket pins. Any inadequate clearances identified should be rectified (paragraph 129a).

- 5 *The purpose of this recommendation is to ensure that National Express Midland Metro identifies OLE components that may affect the safe operation of the tramway and controls any changes made to them.*

National Express Midland Metro should identify those OLE components which may affect the safe operation of the tramway. It should review the current processes and practices intended to control changes to these components and implement any actions required to ensure that effective change control is exercised in the future (paragraphs 129a and 131a).

The following recommendations are linked solely to additional observations:

- 6 *The purpose of this recommendation is to ensure that any risks created by a driver becoming incapacitated during an incident are assessed and that appropriate mitigation measures are adopted by National Express Midland Metro.*

National Express Midland Metro should assess what, if any, risks would be created by a driver becoming incapacitated during an incident. It should identify and implement appropriate measures to manage any identified risks, such as additional training for CSRs (paragraph 131b).

continued

- 7 *The purpose of this recommendation is to ensure that the mandatory competencies of drivers and CSRs are assessed and that those found critical to the safe operation of the Midland Metro are subject to a competence management system that ensures they are achieved and maintained.*

National Express Midland Metro should review the current mandatory competences held by drivers and CSRs in order to identify those which are essential to the safe operation of the Midland Metro. It should identify and implement appropriate measures to ensure that all such competences are maintained (paragraph 131d).

Appendices

Appendix A - Glossary of abbreviations and acronyms

CCTV	Closed Circuit Television
CSR	Customer Service Representative
NXMM	National Express Midland Metro
NXWM	National Express West Midlands
OLE	Overhead Line Equipment
ORR	Office of Rail Regulation
PRIMOS	Primary Member Of Service

Appendix B - Glossary of terms

All definitions marked with an asterisk, thus (*), have been taken from Ellis's British Railway Engineering Encyclopaedia © Iain Ellis. www.iainellis.com.

Aramid fibre	A high strength synthetic fibre used to form the core of Parafil rope.
Automatic dropping device (ADD)	A protection device fitted to a pantograph which lowers it if it should be raised above a set maximum height limit (ie if it is no longer touching the contact wire) or if the contact strip becomes damaged. The operation of the device may limit damage to the OLE.
Auto-tensioner	A device which maintains a contact wire at a constant tension by compensating for thermal expansion and contraction over a specified range of temperatures.
Blow-off	The lateral displacement of a tensioned rope or wire within an OLE system due to the effect of the wind.
Bracket arm	A form of OLE support where a horizontal arm (known as the cantilever) attaches at one end to an OLE pole at side of the tramway and is supported vertically by tie ropes. The contact wire is directly suspended from the cantilever.
Bracket foot assembly	The part of a bracket arm which fits into the OLE pole bracket at one end and into the steel tubular cantilever at the other and thus connects the two. It consists of the clevis cover, an insulator and a reducing sleeve.
Cantilever	The horizontal arm within a bracket arm type OLE support.
Cess	The space directly alongside the tramway.
Clevis	Part of the pole bracket, this is a type of a fastening consisting of top and bottom prongs which form a U shape and through which directly opposite holes have been created. The tang of the clevis cover fits in-between the prongs and is held in place via the clevis pin, which fits through the holes in the prongs and the tang to form the complete fastening.
Clevis cover	Part of the bracket foot assembly, made of aluminium bronze. One end is formed to make a tang which fits into the clevis of the pole bracket and is held in position by the clevis pin. The other end is threaded internally to accept the insulator.
Clevis pin	The pin which fits through the holes drilled through the prongs of the clevis and the tang of the clevis cover and which fastens the cover into position.
Contact wire	The wire with which the pantograph makes contact in order to collect current.

Customer service representative (CSR)	The member of a tram's crew whose primary duty is to provide information to passengers and to collect revenue.
Data recorder	A device fitted onboard trams which records data relating to their speed and the operation of their controls and safety systems.
Delta suspension	A 7 mm diameter Parafil rope which suspends the contact wire from the cantilever. Held at its apex either within a clamp or allowed to run freely over a plastic pulley. Both of which connect to a bracket on the cantilever via shackles and/or quick links. Also known as a bridle.
Finite Element Analysis	A computer based technique which uses the finite element method to analyse the effects of the forces applied to an object.
Hazard brake	A brake that provides a high rate of retardation for use in emergency situations. The rate is higher than would normally be acceptable to passengers.
Headspan	A type of OLE support structure where the contact wire is attached to a transverse span-wire. This is attached at either end to OLE structures and provided with extra support from above (via Parafil droppers) by a transverse head-span wire.
Hydrolysis	A process in which water breaks down aramid fibres into their constituent chemicals. This reduces their mechanical strength and may ultimately turn the fibres into a powder.
Incident Officer	A designated member of NXMM staff who attends the scene of a tramway incident in order to manage on-site activities and liaise with other agencies.
In-running	The tension length of contact wire which is commencing with respect to a particular direction of travel.
Insulator	A porcelain or polymer device used to isolate the live parts of an OLE system from its supports.*
Line-of-sight	A method of operating in which the driver observes the line ahead and controls the tram's speed so that he or she is able to stop using the service brake before reaching a reasonably visible obstruction.
Metallurgical creep	The permanent elongation of a conductor due to it being under tension over a period of time.
Office of Rail Regulation (ORR)	The safety authority for railways and tramways in Great Britain.
Off-street running	A portion of a tramway network in which the track has a separate alignment to the highway and is completely segregated from it.

On-street running	A portion of a tramway network in which the track is laid within the boundaries of a highway and which can be crossed by pedestrians and other vehicles either generally or only at designated crossing points.
Operating load	The total of the self-weight, radial and variable loads within the OLE. Also known as the normal or permanent load.
Out-of-running	The tension length of contact wire which is terminating with respect to a particular direction of travel.
Overhead Line Equipment (OLE)	An assembly of metal conductor wires, insulating devices and support structures used to bring a traction supply current to suitably equipped trains or trams.*
Overlap	The change-over point between two adjacent tension lengths of contact wire.
Pantograph	A device fitted to the roof a tram or train which contacts the contact wire of the OLE, allowing the vehicle to draw current.*
Parafil	The proprietary name of a type of synthetic rope which consists of a core of high-strength aramid fibres lying in parallel, enclosed within various types of polymeric protective sheath.
Parallel feeder wires	Additional along-track conductors which run parallel to, but separate from, the contact wires. These conductors increase the effective cross-sectional area of the contact wires and thus reduce their electrical resistance. Also known as aerial feeders.
Pole Bracket	A bracket mounted on an OLE pole, the clevis of fastens the clevis cover of the bracket foot assembly.
Primary Member Of Service (PRIMOS)	The NXMM member of staff who will take charge of an incident on behalf of the tramway and liaise with other agencies pending the arrival of an Incident Officer.
Radial load	The load within the OLE which is created by the force of tensioned wires and ropes when they run at an angle to the centre line of the track. The magnitude of the load is related to the tension of the wire or rope, the distance between supports and the radius of any curve, towards whose centre this load will always act.
Reducing sleeve	A cast sleeve with internal threads which accepts the insulator (at its smaller diameter end) and the thread cut into the exterior of the cantilever tube (at its larger diameter end).
Register	The lateral position of the contact wire above the track.
Register arm	An OLE component which attaches at one end to the bracket arm and to the contact wire at the other. Allows the wire to lift under the force of a pantograph whilst maintaining it in the correct register. Also known as a steady arm.

Safety validation	The framework within which NXMM considers proposed changes. Intended to provide an auditable record of decisions taken, to ensure compliance to standards and to identify any new or increased risks and any safety controls and mitigation measures required.
Self-weight load	The load within the OLE which is created by the weight of the OLE equipment itself.
Span-wire	A type of OLE support structure where the contact wire is suspended via a delta suspension and register arm from a transverse wire which is attached at either end to buildings or structures.
Stagger	An intentional variation in contact wire register with respect to the centre line of the track created at an OLE support. Ensures that the contact wire sweeps across the width of pantograph heads and wears them evenly.
Tang	Part of the clevis cover which fits between the prongs of the pole bracket clevis and through which a hole has been created. Held in place by the clevis pin.
Ten foot	The space between two pairs of tracks on a four-track railway.
Tension length	A section of contact wire running between its tensioner and anchor point.
Tie ropes	Metal or synthetic ropes which provide vertical support for the cantilever on a bracket arm and which attach to the OLE pole.
Variable load	The load within OLE which is created by factors such as ice or wind.
Wire-height	The height of the underside of the contact wire above a reference rail when being lifted by a pantograph.
Yield	The point at which a component under stress transitions between elastic and plastic behaviour.

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Department for Transport.

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