Railway Accident
Investigation Unit
Ireland

INVESTIGATION REPORT

Luas Overhead Line Failure, Stillorgan,

2nd November 2020

RAIU Investigation Report No: 2021 – R006

Published: 27th October 2021

Report Description

Report publication

Where the report has been altered following its original publication, details on the changes will be given.

For further information, or to contact the RAIU, please see details below:

RAIU
2nd Floor, 2 Leeson Lane
Dublin 2
Ireland

email: info@raiu.ie
website: www.raiu.ie
telephone: + 353 1 604 1050

Report structure

The report structure is taken from guidelines set out in "Commission Implementation Regulation (EU) 2020/572 of 24 April 2020 on the reporting structure to be followed for railway accident and incident investigation reports" having regard to "Directive (EU) 2016/798 of the European Parliament and of the Council of 11 May 2016 on railway safety".

Reader guide

All dimensions and speeds in this report are given using the International System of Units (SI Units). Where the normal railway practice, in some railway organisations, is to use imperial dimensions; imperial dimensions are used, and the SI Unit is also given.

All abbreviations and technical terms (which appear in italics the first time they appear in the report) are explained in the glossary.

Descriptions and figures may be simplified in order to illustrate concepts to non-technical readers.

Preface

The RAIU is an independent investigation unit within the Department of Transport (DOT) which conducts investigations into accidents and incidents on the national railway network, the Dublin Area Rapid Transit (DART) network, the LUAS light rail system, heritage and industrial railways in Ireland. Investigations are carried out in accordance with the Railway Safety Directive (EU) 2016/798 enshrined in the European Union (Railway Safety) (Reporting and Investigation of Serious Accidents, Accidents and Incidents) Regulations 2020 and the Railway Safety (Reporting and Investigation of Serious Accidents, Accidents and Incidents Involving Certain Railways) Act 2020.

The RAIU investigate all serious accidents. A serious accident means any train collision or derailment of trains, resulting in the death of at least one person or serious injuries to five or more persons or extensive damage to rolling stock, the infrastructure or the environment, and any other similar accident with an obvious impact on railway or tramline safety regulation or the management of safety. During an investigation, if the RAIU make some early findings on safety issues that require immediate action, the RAIU will issue an Urgent Safety Advice Notice outlining the associated safety recommendation(s); other issues may require a Safety Advice Notice.

The RAIU may investigate and report on accidents and incidents which under slightly different conditions might have led to a serious accident.

The RAIU may also carry out trend investigations where the occurrence is part of a group of related occurrences that may or may not have warranted an investigation as individual occurrences, but the apparent trend warrants investigation.

The purpose of RAIU investigations is to make safety recommendations, based on the findings of investigations, in order to prevent accidents and incidents in the future and improve railway safety. It is not the purpose of an RAIU investigation to attribute blame or liability.

Summary

On 2nd November 2020 the 14:31 hours (hrs) Luas Service 65 (operated by Tram 5010) from Brides Glen to Broombridge served Stillorgan inbound platform before moving forward to Signal B11. The driver of Tram 5010 (Driver 5010) noticed the Main Circuit Breaker (MCB) had opened in the driving cab (the MCB opened due to its failure to detect 750 volts (V) *Direct Current* (DC) from the Overhead Contact System (OCS)). The loss of 750V DC was the result of the OCS *Electrical Supply System*, *High Speed Circuit Breaker* (ESS HSCB) L1 (L1 signifies into the City Centre) Sandyford opening automatically due to the OCS breaking and short circuiting against the roof of Tram 5010. Driver 5010 also noticed the OCS was sagging and advised the Traffic Supervisor at the Luas Network Management Central (LNMC).

The Traffic Supervisor viewed the images from the Close Circuit Television (CCTV) cameras located at the Stillorgan Stop and saw the OCS had broken and was lying across the top of Tram 5010, the outbound track and platform. The Traffic Supervisor instructed Driver 5010 not to open the passenger doors and to keep all passengers inside the tram until otherwise advised. The *Supervisory Control And Data Acquisition* (SCADA) system indicated that the section in the area of Stillorgan was *de-energised.*

The Traffic Supervisor identified other trams operating in the vicinity of Stillorgan and requested they stop; which they did. Shortly afterwards, the Traffic Supervisor began attempting to reform service and requested that Service 88, Brides Glen to Parnell, (operated by Tram 5003) continue to Sandyford Stop and stop there. At approximately 14:37 hrs, Tram 5003 passed the *Insulated Overlap* (two OCS contact wires from two electrical sections which provide a continuous supply of power to the tram when the tram passes from one section to the next and also allows for de-energising of one section at a time) between Sandyford and Central Park. As the pantograph head of Tram 5003 traversed the Insulated Overlap, the pantograph bridged both contact wires and electrically connected the two sections together, re-energising the section at Stillorgan where Tram 5010 was located. The re-energising of the section at Stillorgan resulted in a second short circuit between the OCS wire and the roof of Tram 5010. The second short circuit resulted in HSCB L2 (L2 signifies out of City Centre) Sandyford and HSCB L1 Glencairn also tripping out due to overcurrent.

The On Tram Data Recorder (OTDR) download was requested by the RAIU but the data relating to the incident was overwritten and not available as Transdev had not downloaded the data post-incident.

In this incident, there are two distinct events, namely the failure of the OCS wire and the re-energisation of the failed OCS wire, and as such the causal, contributing and systemic factors are separated. In terms of the OCS mechanism of failure, the OCS wire failed for the following causal factors (CaF):

- CaF-01 - The OCS wire at Stillorgan suffered from necking (reducing its tensile strength) as a result of the OCS wire becoming annealed due to over-heating;
- CaF-02 – The planned inspections of the OCS did not identify the presence of necking at the Stillorgan Stop.

Contributory factors (CoF) include:

- CoF-01 – The inspections of the OCS did not identify the presence of Cupric Oxide as a precursor to the necking, either at Stillorgan in 2020 or at Milltown in 2015;
- CoF-02 – The stopping position of trams, consistently in the same location (15 m or 30 m from the Stop Line) resulted in the pantograph drawing down the current at the same location on the OCS wire.

A systemic factor (SF) was identified as:

- SF-01 – The OCS inspection regime was not robust and failed to identify OCS wire necking, as evidenced at numerous locations on the Green Line.

The re-energisation of the broken OCS wire at Stillorgan was a result of:

- CaF-03 – Service 88 (Tram 5003), although initially stopped by the Traffic Supervisor, was permitted to continue to Sandyford Stop; while travelling to Sandyford, the pantograph of Tram 5003 bridged the Insulated Overlap between Sandyford ESS and Central Park.

There are no contributing factors associated with this incident in terms of the re-energisation of the broken OCS wire.

Systemic factors were:

- SF-02 – The Dewirement Guide did not provide enough details for the Traffic Supervisor to manage a dewirement incident appropriately;
- SF-03 – The Incident Management Procedure only provides information for larger incidents, and as such did not provide information in relation to dewirements incidents where there are no fatalities or injuries.

As a result of the above findings, the RAIU made five safety recommendations:

- Safety Recommendation 202106-01 – Transdev, along with S2M, should conduct a full review of their inspection processes for OCS wires to ensure pre-cursors, likely location and faults with the OCS are referenced;
- Safety Recommendation 202106-02 – Transdev should conduct a full review and update of their dewirement/incident management documents, to ensure that dewirement incidents are fully addressed; in particular in relation to zone identification for de-energised sections of track in the event of an incident. These documents should then be fully briefed to the Traffic Supervisors;
- Safety Recommendation 202106-03 – Transdev should put a process in place that all trams involved in serious incidents have the OTDR downloaded as soon as possible to prevent overwriting of the data.
- Safety Recommendation 202106-04 – Transdev should include the electrical resistance measuring of vehicle earth bonding in the planned preventative maintenance regime for all trams.
- Safety Recommendation 202106-05 – Transdev should investigate the reason for the build-up of Cupric Oxide on the OCS wire. The investigation should include but not limited to:
  - Impact of longer trams, and congestion of trams in electrical sections;
  - Electrical resistance monitoring of tram to identify if high current demand is an issue;
  - Consequence of trams working in degraded mode on current demand;
  - The pantograph carbon bands and OCS interface.

Contents

RAIU Investigation

RAIU decision to investigate

1 In accordance with the Railway Safety (Reporting and Investigation of Serious Accidents, Accidents and Incidents Involving Certain Railways) Act 2020 (No. 18 of 2020) with reference to S.I. 430 of 2020 Regulation 5 (5), the RAIU investigate *serious accidents*, the RAIU may also investigate and report on *accidents* and *incidents* which under slightly different conditions might have led to a serious accident.

2 The RAIU on-call investigator received a notification of a failure with the OCS at Stillorgan inbound platform on 2nd November 2020. After the RAIU conducted a Preliminary Examination, the RAIU's Chief Investigator (CI) made the decision to conduct a full investigation into the failure, given its impact on railway safety (S.I. 430 2020 Regulation 6(2)(b)). as under slightly different circumstances the failure may have led to serious accident with the potential for fatality or serious injuries due to a live wire falling on to the platform.

3 If classified under the EU Agency for Railways categorisation, this occurrence would be considered: Incident – Energy.

4 The RAIU's CI allocated RAIU Senior Investigators, trained in accident investigation, to conduct this investigation, as appropriate. In this instance, the RAIU engaged a metallurgical specialist consultant to examine and report on the failed sections of the OCS.

Scope & limits of investigation

5 The RAIU have established the scope and limits of the investigation as follows:

- Establish the sequence of events leading up to the failure;
- Identify any other precursors which led to the failure;
- Establish, where applicable, causal, contributing and systemic factors;
- Examine the failure mode of the OCS;
- Examine the relevant operation standards and procedures in relation to failures of the OCS.

Communications & evidence collection

6 During the investigation, the RAIU collate evidence through the submission of Requests For Information (RFIs) and interviewing. Related to this investigation, the RAIU collated and logged the following evidence:

- CCTV of the incident from Stillorgan Stop;
- Witness statements from parties involved in the failure;
- Maintenance specifications for the pantograph from Transdev Dublin Light Rail (to be known as Transdev for the remainder of this report);
- Maintenance records for the inspection and repair of the OCS on the Green Line;
- Event log from the Traction Power Supply, SCADA system;
- Analysis of the failed OCS wire report by the RAIU metallurgical specialist consultant (ms4i), “Contact wire from the overhead line equipment of Dublin’s Luas tram system failure analysis report”.
- S2M (Joint Venture Systems Maintenance Team) Report, “Overhead line failure at Stillorgan tram stop 02/11/20”.

7 All relevant parties co-operated fully with the RAIU investigation; with no difficulties arising.

Other stakeholder inputs

8 An Garda Síochána attended the incident site at Stillorgan and cordoned off the area.

9 Dublin City Council were also notified of the incident.

Other information relevant to the investigation process

10 The RAIU engaged a metallurgical specialist (ms4i) to analyse the failed OCS wire and a report was produced.

RAIU report format

11 The RAIU report is divided into a number of key sections, namely:

- Summary of the failure & background information – which provides factual information surrounding the incident, including:
    - Synopsis of the incident, which provides an abridged version of failure events;
    - External circumstances surrounding the failure or accident location (such as weather conditions or location geography);
    - Consequences of the failure, including fatalities, injuries or material damage;
    - Parties and roles associated with the incident;
    - Description of the relevant parts of infrastructure, rolling stock, signalling and communications, operations or other equipment associated with the incident.
- Evidence – which provides further factual details on supporting information for the background information, for example, this section may include details on: Safety Management Systems, standards and procedures; risk assessments, etc;
- Events before, during and after the accident – which gives a chain of events:
    - Leading up to the occurrence including actions taken by persons involved; the functioning of rolling stock and technical installation and the operating system;
    - During the occurrence, by describing the occurrence;
    - After the occurrence including: occurrence consequences; measures taken to protect the occurrence site; and, the efforts of the rescue and emergency services.
- Similar occurrences – which outlines occurrences similar in nature to the occurrence subject to this report.
- Analysis – which analyses the combined findings from the above established facts, such as: roles and duties; rolling stock and technical installations; human factors; feedback and control mechanisms; and, trends related to similar occurrences.
- Conclusion – which includes: concluding information from the analysis of the factual findings; measures taken since the occurrence; additional observations.
- Safety Recommendations – where appropriate, safety recommendations will be made with the sole aim of preventing a similar occurrence in the future; safety recommendations may also be made as a result of additional observation with the aim of prevent another type of occurrence. The absence of safety recommendation shall be explained.

Summary of the failure & background information

Synopsis of the incident

12 On 2nd November 2020 Luas Service 65, operated by Tram 5010, served Stillorgan inbound platform at 14:31:52 hrs.

13 At 14:34:27 hrs Tram 5010 moved forward to Stillorgan inbound signal, Signal B11.

14 At 14:34:59 hrs the OCS broke while Tram 5010 was stopped at Signal B11. The broken OCS wire fell on the roof of Tram 5010 resulted in OCS ESS HSCB Sandyford L1 (into City Centre) short circuiting, opening the MCB on Tram 5010 (as the tram could not detect the 750 V DC from the OCS) and de-energising the section.

15 Driver 5010 observed the OCS sagging and contacted the Traffic Supervisor at LNMC.

16 The Traffic Supervisor viewed the CCTV cameras at Stillorgan Stop and saw that the OCS had detached with one end two meters above the roof of Tram 5010 and the other end resting on the roof of Tram 5010 and the outbound track and platform at the Stillorgan Luas Stop. The Traffic Supervisor also saw that the section was de-energised by looking at SCADA system screen.

17 The Traffic Supervisor identified trams in the vicinity of Stillorgan and requested them to stop; soon afterwards the Traffic Supervisor began to allow the trams move to their next stops in order to reform service.

18 Luas Service 88[1], operated by Tram 5003, departed Central Park inbound stop at approximately 14:34 hrs and was advised by the Traffic Supervisor to stop at Sandyford Stop and tell passengers the service was terminating there.

19 At 14:37:31 hrs, Tram 5003 entered the Insulated Overlap between Sandyford ESS and Central Park (the Insulated Overlap is on the approach to Sandyford Stop the locations the Traffic Supervisor advised Tram 5003 to terminate) with the pantograph bridging both sections of wire, resulting in the de-energised section at Stillorgan Stop re-energising.

20 When the current was restored to the broken wire, the section of OCS wire resting on the roof of Tram 5010 short circuited against the roof of Tram 5010.

21 The Traffic Supervisor requested S2M (Joint Venture Systems Maintenance Team) to put on an emergency isolation to facilitate passengers disembarking from the tram.

[1] Service L 88 – Brides Glen to Parnell

External circumstances at the incident location

Weather

22 The weather was dry and fine; weather data was taken from the nearest Met Éireann Weather Station at Phoenix Park, 13 kilometres (km) north-west of Stillorgan Stop, recorded that there was no rainfall at the time of the incident. The maximum temperature was recorded at 14ºC, and mean wind speed was recorded at 10.7 knots.

23 The weather conditions were not contributory to the incident.

Fatalities, injuries & material damage

Fatalities & injuries

24 There were no fatalities or injuries to staff or passengers as a result of the incident.

Material damage

Tram 5010

25 The roof of Tram 5010 suffered arc burning and the *pantograph carbon bands* had to be replaced.

OCS

26 Twenty-nine meters of contact wire from the OCS and the parafil cross spans on both sides of the OCS wire break had to be replaced.

Other consequences as a result of the incident

27 As a result of the incident Green Line trams operated on the south-side of the failure from Brides Glen to the Gallops; and, on the north-side from Broombridge to Beechwood for approximately eight hours while the OCS was being repaired.

Parties & roles associated with the incident

Parties involved in the incident

28 Transdev operates the Luas light rail tram system in Dublin. As of the 1st December 2019, Transdev are the Vehicle Maintenance Contractor (VMC) and Infrastructure Maintenance Contractor (IMC); and they also provide security staff.

29 S2M carry out infrastructure maintenance for Transdev. S2M is a joint venture between Transdev and Efacec[2] formed to deliver power and systems maintenance for the Luas infrastructure. There are four disciplines: Track; Overhead Line (OHL); Traction Power; and, Communications. The Infrastructure Technicians report to a Discipline Supervisor who reports to a Discipline Manager. The four Discipline Managers report to the Joint Venture Manager who in turn reports to the Head of Infrastructure. Transdev provides shared services to S2M including human resources, planning, procurement and safety.

Roles involved in the incident

30 Driver 5010 is employed by Transdev. Driver 5010 has been trained and is deemed competent to drive Luas trams and has approximately four years' driving experience. Driver 5010 passed their last assessment (with no restrictions) on the 30th December 2019[3].

31 The Luas driver of Tram 5003 (to be referred to as the Driver 5003 for the remainder of this report) is employed by Transdev. Driver 5003 has been trained and is deemed competent to drive Luas trams. Driver 5003 has approximately ten years' driving experience and passed their last assessment (with no restrictions) on the 12th February 2020.

32 The Traffic Supervisor, based in the Red Cow LNMC, is employed by Transdev. At the time of the incident, the Traffic Supervisor had been trained and was deemed competent to carry out Traffic Supervisor duties. The Traffic Supervisor had fifteen years' experience in the Traffic Supervisor's role and passed his last assessment (with no restrictions) on 21st July 2019[4].

---

[2] Efacec is a Portuguese company with 70 years' experience focusing on the development of products and systems for the infrastructural sectors as energy, environment, industry mobility and transport with a presence in over sixty-five countries.

[3] A number of drivers' annual assessments were delayed as a result of Covid-19 restrictions.

[4] A number of Traffic Supervisors' annual assessments were delayed as a result of Covid-19 restrictions.

General description of the tramway

33 Dublin's Luas network is made up of the Red and Green Lines; the network has sixty-seven stop and 44.5 kilometres (km) of track, see Figure 1.

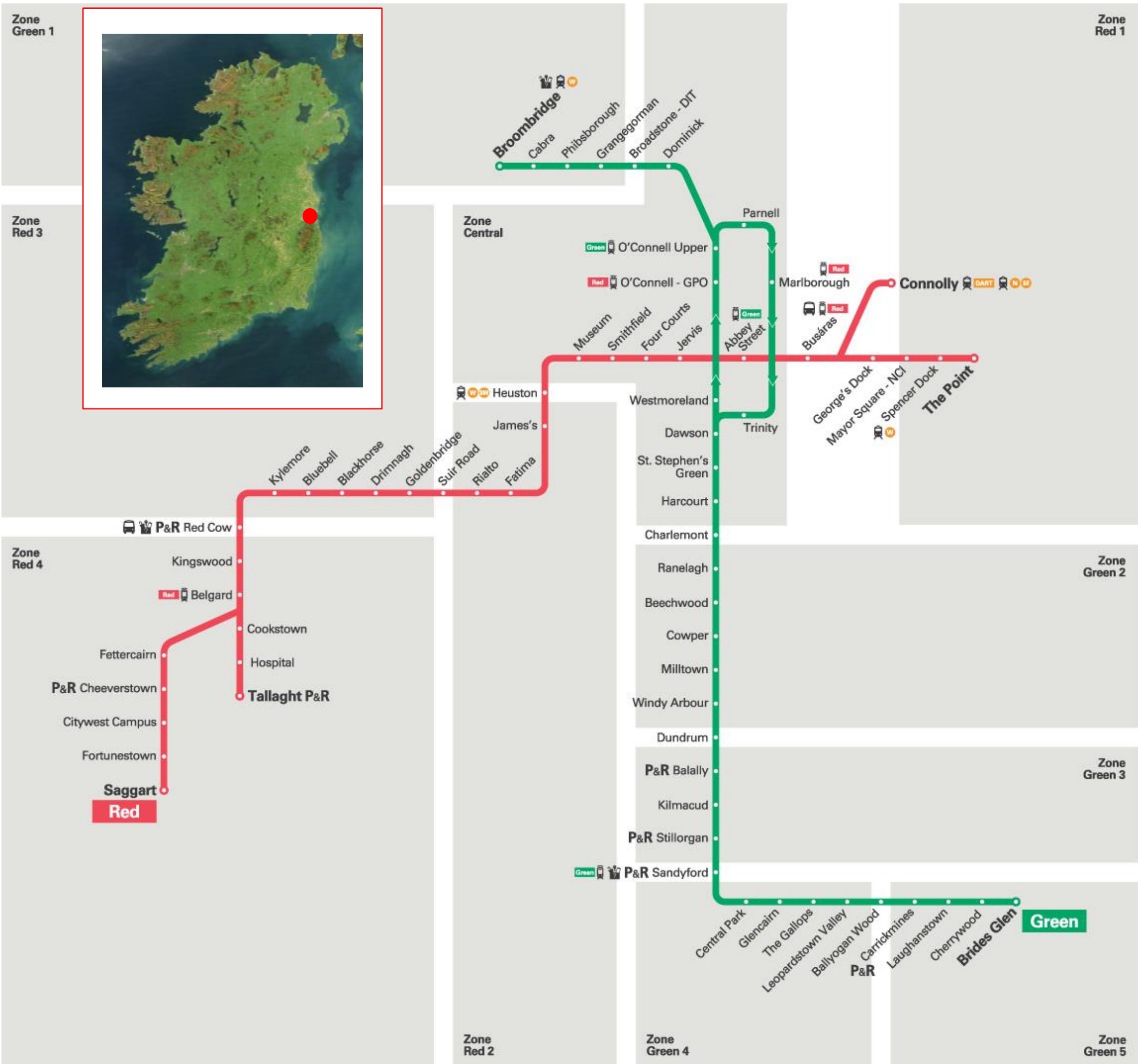

Figure 1 – Luas network map

34 The Red Line is 20 km in length and has thirty-two stops running from Tallaght to The Point and from Saggart to Connolly. The Green Line (where Tram 5010 was operating) is 24.5 km in length and has thirty-five stops running from Brides Glen to Broombridge via the City Centre.

35 Trams operate on a combination of separated track, segregated track and shared running (where the trams share the road with other road users).

36 The lines are generally double track lines, with the exception of certain areas e.g. O'Connell Street and Dawson Street.

37 Trams are powered by an OCS providing 750 V DC delivered from twenty electrical sub-stations, the OCS is discussed further in paragraphs 59 to 63.

38 Stillorgan Stop is located on the Green Line. Trams stop and start at the defined position on the platform (see Figure 2 for stopping position markings at Stillorgan Stop).

Figure 2 – Yellow dots indicating the stopping position for trams at Stillorgan

39 Transdev tram stops are fitted with a CCTV system that allows for live viewing by the Traffic Supervisor as well as recording and play back facility. The CCTV footage at Stillorgan Stop is date stamped but not time-stamped.

Rolling Stock

40 Tram 5010 is one of the twenty-seven "502" tram fleet operating on the Green Line in Dublin. The 502 trams are 54.6 m long, 2.4 m wide, 3.45 m high (with the pantograph lowered).

41 The 502 trams consist of nine modules: four motorised, one trailer car and four suspended units, see Figure 3.

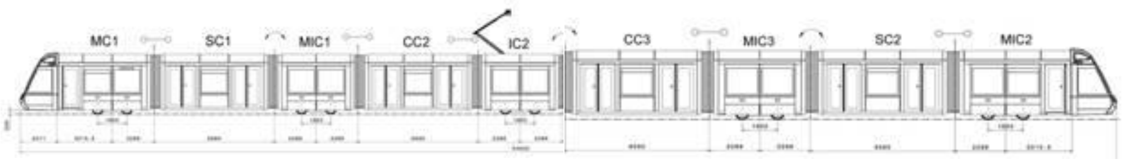

Figure 3 – 502 Tram configuration

42 Luas "402" trams, consisting of seven modules and a length of 43.6 m, also operate on the Green Line.

43 One pantograph connects the tram to the OCS irrespective of the number of modules that make up the complete tram; the pantographs are discussed further in paragraphs 48 to 51.

44 The On Tram Data Recorder (OTDR) download was requested by the RAIU but the data relating to the incident was overwritten and not available as Transdev had not downloaded the data post-incident. The data on the OTDRs is overwritten between 42 km and 53 km, depending on the type of tram; by way of example the average weekday kilometres, per tram, on the Green Line is 253 km[5].

Signalling & Communications

45 Trams movements are regulated through the use of line side signals which must be obeyed by tram drivers and other road users. The signals, normally positioned to the left of the leading driving cab on the kerb, are provided by an array of light emitting diodes (LED) which are lit according to the type of signal to be displayed e.g. horizontal (stop), vertical (proceed). Tram signals and regulatory stationary signs are set out in the Department of Transport's Traffic Signs Manual, last updated in August 2019.

[5] The RAIU have identified this as an Additional Observation, AO-01 (paragraph 154), and made a Safety Recommendation, Safety Recommendation 202102-03 (paragraph 167).

46 The means of communication between tram drivers and the LNMC is by Tetra radio and lineside help points.

Operations

47 Trams are regulated on track by “line-of-sight driving” where the driver is responsible for observing and maintaining a sufficient distance from trams ahead, motor vehicles, pedestrians, hazards or obstacles that are present or can be expected to be present on the track so the driver can stop the tram without causing a collision.

Evidence

Luas Pantograph

General description

48 The pantograph (Figure 4) is an articulated, mechanical assembly that facilitates the pickup of current in the OCS wire and transfers it to the hight tension supply cabinet, called the Collector Circuit Breaker cabinet. Luas pantographs are manufactured by Schunk Transit Systems.

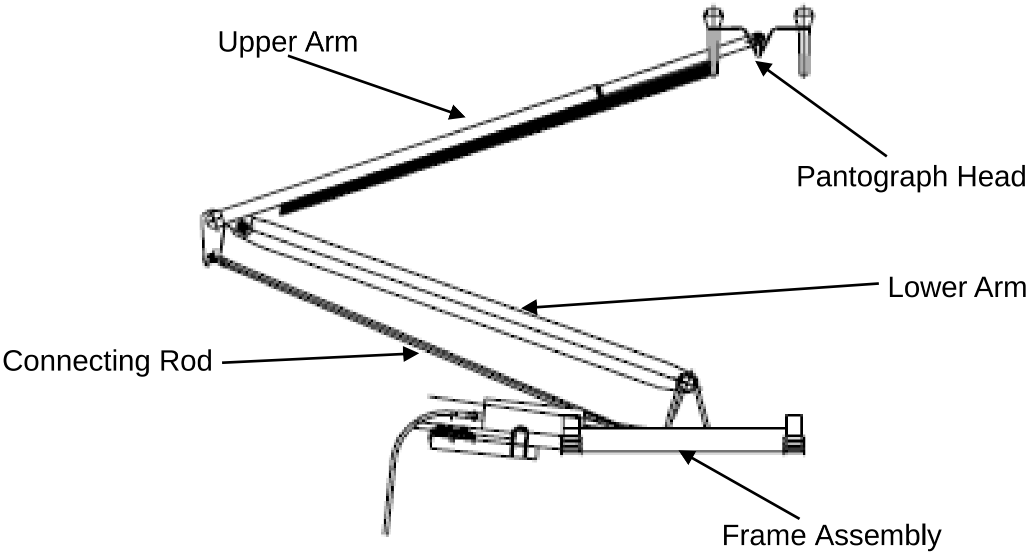

Figure 4 – Illustration of the pantograph assembly fitted to 502 Trams

49 When raised the spring assembly pushes the head upwards against the contact wire, and the entire pantograph assembly is live at the supply voltage of 750V DC. The assembly is insulated from the tram by four securing insulator assemblies.

50 Carbon bands are a long-extruded carbon fitted into an aluminium carrier that is provided on top of the pantograph and collects current from an overhead wire. This is the point of interface between the tram and the OCS[6].

51 The earthing of the tram is achieved through earth connection and inter module earth bonds ensuring a good electrical connection between the body of the tram and the wheelset.

[6] Schunk Transit Systems advise that carbon band damage is most likely the result of an OCS or pantograph faults as the carbon bands are the weakest point in the configuration.

Pantograph inspection and maintenance

52 Pantographs are maintained by Transdev at intervals of 15,000 km, 60,000 km and 600,000 km.

53 Vehicle earth bonding are visually inspected at 60,000 km but the vehicle maintenance exams do not require the electrical resistance of the earth bonding to be measured[7].

54 Tram 5010 received its last maintenance intervention prior to the incident on the 14th October 2020. No faults were reported against the pantograph.

Post-incident inspection of the pantograph

55 The pantograph of Tram 5010 was inspected post-incident and no faults were found. The pantograph lowered and raised smoothly, and the carbon bands were adequate.

56 The top, mid and lower pantograph's uplift pressures were recorded as 8.3 kg, 7.8 kg and 8.2 kg, respectively, with an average of 8.1 kg. The pressure is within the specified parameters of between 7.65 kg to 9.7 kg, as set out in Transdev document TDLR-LUAS-WI-00652, "Check of upward contact force of the bow on the of the catenary", Issue E, published in October 2015.

Post-incident inspection of other pantographs on the Green Line

57 All thirty-two trams operating on the Green Line had the pantograph carbon bands checked post incident, with two trams (Tram 5019 and Tram 5024) requiring the carbon bands to be replaced and re-checked after one day running with no further fault found.

58 At the time of the incident Tram 5019 was working approximately thirty minutes to the rear of Tram 5010; and was identified, by a passing driver, to be "sparking" and was tow-pushed to the depot for inspection, which found the pantographs top, mid and lower uplift pressures to be within specification (paragraph 56).

[7] The RAIU have identified this as an Additional Observation, AO-02 (paragraph 154) and have made a safety recommendation, Safety Recommendation 202102-04, (paragraph 167).

Luas Overhead Contact System

General description

59 Trams are powered by an OCS providing 750 V DC delivered from twenty electrical sub-stations; power is supplied to the sub-stations from the national grid at 10 kilovolts (kV) *alternating current* (AC). The 750 V DC supplied to the trams via a roof mounted pantograph is converted to AC to power the motorised bogies on the tram set. The return circuit is through the wheel rail interface and back to the sub-station.

60 The maximum heigh of the contact wire is 6.59 metres (St. Stephen’s Green) above rail level decreased to a minimum of 3.97 metres (Dundrum to Balally) at overbridges and other low structures. The contact wire height at Stillorgan was 6.2 m above rail level and not considered as contributory to the incident.

61 The OCS is sectioned electrically to allow maintenance intervention including planned and emergency repair of the OCS without the need to de-energise the complete line.

62 The sectioning between Sandyford ESS and Central Park is achieved by Insulated Overlap at the termination of one wire and the start of the next. The Insulated Overlap provide a continuous supply of power to the tram when the tram passes from one section to the next and also allows for de-energising of one section at a time. The separation between the wires is such that, in the event of a de-energising at one of the sections, there is no possibility of the two sections coming into contact with each other except when bridged by a pantograph. As a pantograph head traverses the Insulated Overlap, the pantograph bridges both contact wires and electrically connects the two sections together; it runs for approximately ten meters on both contact wires, see Figure 5 for a photograph of a tram passing Sandyford ESS and Central Park Insulated Overlap (note that the pantograph is in contact with the OCS from both sections).

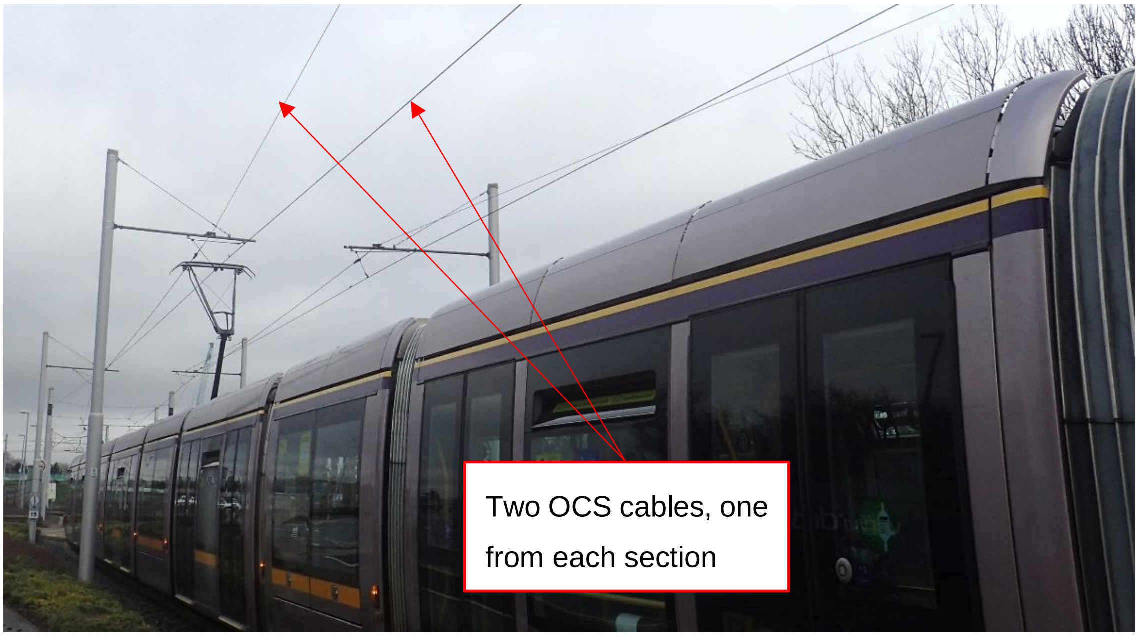

Figure 5 – A tram passing Sandyford ESS and Central Park Insulated Overlap

OCS Inspections

63 OCS inspections are carried out every three months, six months and two years. The inspections consisted of a three monthly ground level OCS inspection, six monthly tension device maintenance, OCS high level inspection including wear measurement and surge diverter inspection. The Stillorgan section received its last inspection between 5th October and the 1st November 2020 with no reports of "*necking*", where there is a decrease in cross-sectional area of the OCS wire due to tensile deformation[8]. This can occur at locations where the pantograph is aligning with the same location of the OCS wire when it is drawing down current to move the tram, for example at stops (paragraph 38, Figure 2) and at signals (e.g. Signal B11).

[8] Narrowing of the cross section of the contact wire over a very short distance (<20mm) and the presence of burn marks or dark rings around the contact wire at the narrowing point are a means of identifying the presence of necking. Necking will most likely occur fifteen or thirty metres from the tram stop line, which corresponds with the position of the pantograph for a seven and nine configuration tram.

Supervisory Control And Data Acquisition

General description

64 LNMC monitor the status of traction power condition for each sub-station and electrified sections. The control and monitoring are carried out by the SCADA system. SCADA is a system of software and hardware elements that allows the LNMC staff to remotely monitor, gather and process real time data in relation to the OCS and record the events into a log file.

65 SCADA displays information on a screen (see Figure 6 for screen shots of SCADA screens), which allows the operator to see the part of the Luas network that is energised, de-energised as well as equipment in failure mode. Commands can be sent to isolate one or more sub-stations or sections of a line. All information relevant to the sub-stations, including fire alarm and intrusion, are also reported on these screens.

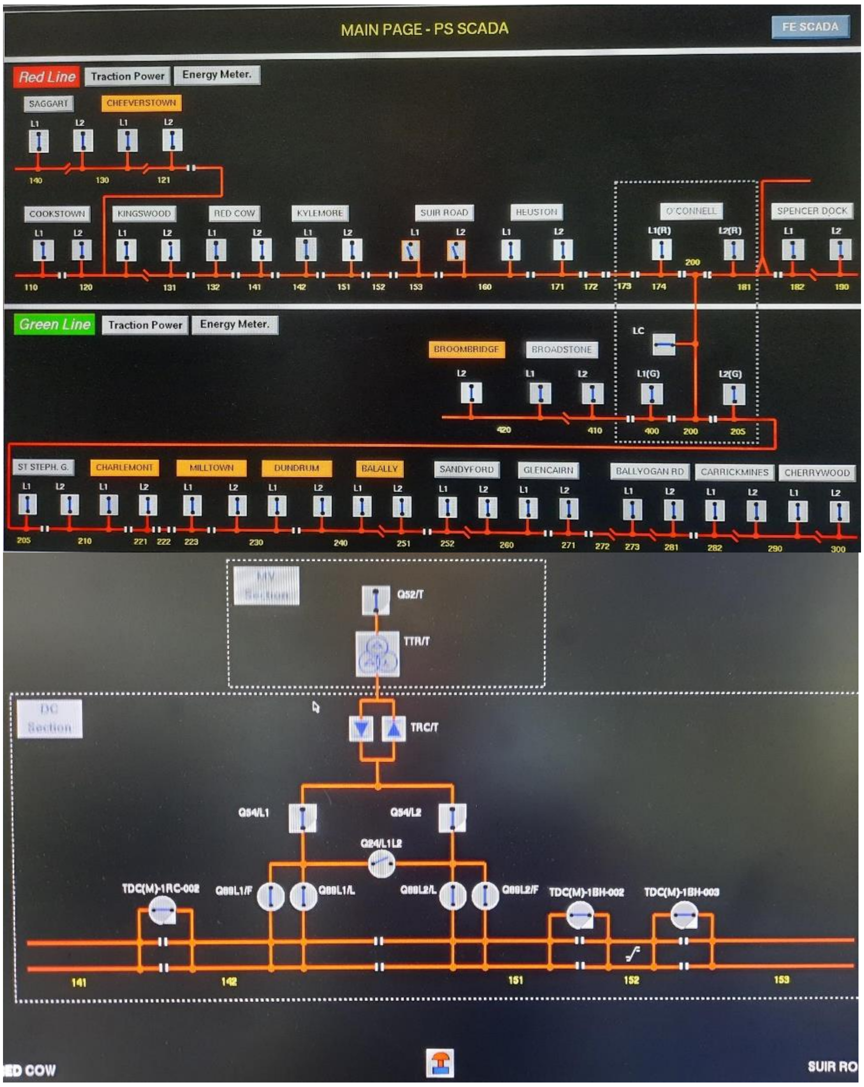

Figure 6 – SCADA screen shots

Post-incident download from SCADA

66 A printout of the SCADA file on 2nd November 2020 from 14:34:59 hrs to 14:37:33 hrs is illustrated in Figure 7. The section highlighted in yellow details the trip out of L1 Sandyford substation and intertrip of Balally; this is a result of the OCS wire parting and short circuiting against the roof of Tram 5010.

67 The section highlighted in green details Tram 5003 entering the Insulated Overlap between Sandyford and Central Park resulting in the re-energising of the L1 Sandyford and Balally section (into the City Centre). The movement resulted in a second short circuit, as the OCS was still resting on the roof of Tram 5010; it also results in L2 Sandyford and Glencairn (out of the City Centre) tripping out due to overcurrent.

Date/Time	Description
02 Nov 2020 14:34:59.000	SANDY ESS TRACTION POWER DISTR HSCB Q54/L1 PS0TAC6AC00009SU00191 BREAKER STATUS OPEN
02 Nov 2020 14:34:59.000	SANDY ESS TRACTION POWER DISTR HSCB Q54/L1 PS0TAC6AC00009SU00190 BREAKER STATUS NOT DEFINED
02 Nov 2020 14:34:59.000	SANDY ESS TRACTION POWER DISTR HSCB Q54/L1 INTERTRIPPING DETECTED
02 Nov 2020 14:34:59.000	SANDY ESS TRACTION POWER DISTR HSCB Q54/L1 OVERCURRENT TRIP DETECTED
02 Nov 2020 14:34:59.000	SANDY ESS TRACTION POWER DISTR HSCB Q54/L1 OVERCURRENT TRIP NOT DETECTED
02 Nov 2020 14:34:59.000	SANDY ESS TRACTION POWER DISTR TDS INBOUND FEED OC0TJ1E0000009SU25290 SECTION 252 - 750 VDC NOT PRESENT
02 Nov 2020 14:34:59.000	SANDY ESS TRACTION POWER DISTR TDS INBOUND LINE OC0TJ1E0000009SU25291 SECTION 252 - 750 VDC NOT PRESENT
02 Nov 2020 14:35:00.000	SANDY ESS TRACTION POWER DISTR HSCB Q54/L1 BREAKER STATUS OPEN
02 Nov 2020 14:36:32.000	SANDY ESS TRACTION POWER DISTR HSCB Q54/L1 INTERTRIPPING NOT DETECTED
02 Nov 2020 14:37:31.000	SANDY ESS TRACTION POWER DISTR HSCB Q54/L2 PS0TAC6AD00009SU00191 BREAKER STATUS OPEN
02 Nov 2020 14:37:31.000	SANDY ESS TRACTION POWER DISTR HSCB Q54/L2 PS0TAC6AD00009SU00190 BREAKER STATUS NOT DEFINED
02 Nov 2020 14:37:31.000	SANDY ESS TRACTION POWER DISTR HSCB Q54/L2 PS0TAC6AD00009SU00130 INTERTRIPPING DETECTED
02 Nov 2020 14:37:31.000	SANDY ESS TRACTION POWER DISTR HSCB Q54/L2 PS0TAC6AD00009SU00132 OVERCURRENT TRIP DETECTED
02 Nov 2020 14:37:31.000	SANDY ESS TRACTION POWER DISTR HSCB Q54/L2 PS0TAC6AD00009SU00132 OVERCURRENT TRIP NOT DETECTED
02 Nov 2020 14:37:31.000	SANDY ESS TRACTION POWER DISTR TDS INBOUND FEED OC0TJ1E0000009SU25290 SECTION 252 - 750 VDC PRESENT
02 Nov 2020 14:37:31.000	SANDY ESS TRACTION POWER DISTR TDS INBOUND FEED OC0TJ1E0000009SU25290 SECTION 252 - 750 VDC NOT PRESENT
02 Nov 2020 14:37:31.000	SANDY ESS TRACTION POWER DISTR TDS INBOUND LINE OC0TJ1E0000009SU25291 SECTION 252 - 750 VDC PRESENT
02 Nov 2020 14:37:31.000	SANDY ESS TRACTION POWER DISTR TDS INBOUND LINE OC0TJ1E0000009SU25291 SECTION 252 - 750 VDC NOT PRESENT
02 Nov 2020 14:37:31.000	SANDY ESS TRACTION POWER DISTR TDS OUTBOUND FEED OC0TJ1E0000009SU25390 SECTION TSG - 750 VDC NOT PRESENT
02 Nov 2020 14:37:31.000	SANDY ESS TRACTION POWER DISTR TDS OUTBOUND LINE OC0TJ1E0000009SU25391 SECTION TSG - 750 VDC NOT PRESENT
02 Nov 2020 14:37:33.000	SANDY ESS TRACTION POWER DISTR HSCB Q54/L2 BREAKER STATUS OPEN

14:34:59 Sandyford substation L1 trips out on overcurrent and intertrips with Balally as a result of a short circuit between the failed OCS cable and the roof of tram 5010.

14:37:31 the OCS is reenergised as a result of tram 5003 entering the Insulated Overlap between Sandyford and Central Park) but as the OCS is still resting on the roof of tram 5010 a second short circuit occurs resulting in L2 Sandyford and Glencairn tripping out on overcurrent.

Figure 7 – SCADA file from 2nd November 2020

Post-incident inspection of the OCS

Green Line

68 Post-incident, high level OCS inspections were carried out on the Green Line, which identified necking at:

- Two locations at Stillorgan Stop – At distances of 15 m and 30 m from the tram stop line;
- Windy Arbour Stop – At a distance of approximately 15 m from the tram stop line;
- Three locations at Sandyford Stop – At distances of 15 m from the tram stop line at two locations & one location 30 m from the tram stop line;
- Glencairn Stop – At a distance of approximately 30 m from the tram stop line;
- Milltown Stop – At a distance of approximately 15 m from the tram stop line;
- Cowper Stop – At distances of approximately 15 m and 30 m from the tram stop lines.

69 Previously scheduled inspections of the OCS on the Green Line failed to detect the presence of necking at the above locations.

70 The 15 m and 30 m distances from the tram stop line corresponds with the location where the seven and nine module trams stop, and the pantographs make contact with the OCS wire for a duration of time, at this location, before it accelerates.

S2M Report

71 Post-incident, S2M produced a fourteen page report into the incident, entitled “S2M Overhead line failure at Stillorgan tram stop 02/11/20”, published in December 2020, to be referred to as the S2M Report for the remainder of this report. The S2M Report identifies the immediate cause of the OCS parting was “because of local overheating caused by the high electric current flowing from the wire to the tram’s pantograph”. The OCS parting was concluded to be as a result of necking (Figure 8), which was “caused by Joule heat due to the current flowing between the contact wire and the pantograph carbon band, through an arc due to poor contact condition. Once the contact wire is softened, its mechanical strength decreases resulting in breakage due to tension force”.

Figure 8 – Image taken from S2M Report

72 The S2M Report states that the second energisation of the wire was due to “the failure to stop all trams in the immediate area entering the de-energised electrical section”.

73 The S2M Report does not reference the black coating on the OCS wire, clearly visible in Figure 8, which is an image which has been taken from the S2M Report.

ms4i Report

74 The RAIU contracted a Metallurgical Specialist, ms4i, to analyse the failed section of the OCS, producing a report entitled “Contact wire from the overhead line equipment of Dublin’s Luas Tram System Failure analysis report TR/21/606” which was published on the 4th May 2021 (to be referred to as ms4i Report for the remainder of this report).

75 A visual examination of the section of the wire that struck the roof of the tram (left hand wire in Figure 9) and short circuited revealed a molten surface whereas the wire that remained hanging from the OCS (right hand wire in Figure 9) exhibited a surface consistent with overloading. It was identified that the OCS wire necked and fractured, in a manner consistent with ductile overload with the fracture surface visually consistent with overloading, with no evidence of stable crack growth mechanism, such as fatigue.

Figure 9 – Images of failed OCS wire from Stillorgan

76 The failed wire was covered with a black coating (see Figure 10) unlike the more accustomed pale green colour patina normally associated with copper oxidation. A sample of the black coating was scraped off the wire and inserted into a scanning electron microscope, fitted with and energy dispersive X-ray microanalyser and identified as Cupric Oxide which forms on copper when it is exposed to a temperature of between 300°C and 400°C and cooled[9]. Repeated occurrences of heating and cooling would result in the copper being annealed. The annealing of the wire would negate the effects of *cold drawing* of the wire during manufacture and reduce its tensile strength.

[9] The RAIU have identified that the reasons for the presence of Cupric Oxide should be determined and have identified this as an Additional Observation, AO-03 (paragraph 154), and made a Safety Recommendation, Safety Recommendation 202102-05 (paragraph 167).

Figure 10 – Close-up of black coating on the OCS wire

77 The Cupric Oxide was tested for electrical conductivity; the test showed that the black coating was insulative at both the contact and non-contact surfaces of the wire.

78 The ms4i Report concluded that:

- The contact wire failed by ductile overloading. It was considered highly likely that repeated occurrences of trams stopping and re-starting at Stillorgan Stop had resulted in sufficient cumulative resistive heating to cause the wire to be locally annealed. This had negated the effects of cold drawing, which had been performed when the wire was manufactured, and reduced its tensile strength. Consequently, the wire failed due to overloading, despite the fact that the tensile load applied to it may have been within normal operating parameters;
- The resistive heating caused the progressive growth of a scale of black Cupric Oxide on the surface of the wire. This increased the effective resistance of the wire and would have exacerbated the resistive heating.

Dewirement Incident Management

79 The Transdev CCR[10] Procedure “Dewirement Quick ref guide” (to be referred to as the “Dewirement Guide” for the remainder of this report), Rev A, published on the 3rd January 2007. It is a one page document, written to assist the Traffic Supervisor in dealing with the high risk uncommon event of dewirement, see Figure 11; a copy is available at the Traffic Supervisor console.

CCR PROCEDURE
Dewirement
Quick ref guide

- De-energise the relevant section of OCS without delay.
    - Zone identification list on back of this page
    - If specific zone cannot be identified clearly, use Emergency de-energisation and then reset HSBC’s in unaffected zones via SCADA.
- Prevent further movement of trams into the affected area.
- Inform Gardai and DCC/SDCC.
- Arrange for IMC to attend to isolate relevant section.
- Dispatch On-Call officer to the scene to assist.
- Detram passengers in a controlled manner away from any OCS wire.
- Ensure driver/staff keep area clear and keep a safe distance from OCS wire.
- Arrange for VMC to attend to examine the tram.
- Record details of any 3rd party vehicles involved in the incident
- Make PA announcements and post PID message.
- Reform the service around the affected section.

Figure 11 – Dewirement Quick ref guide

DCC – Dublin City Council; SDCC – South Dublin City Council; PA – Public Announcement; PID – Public Information Display

HSBC should read HSCB

[10] Central Control Room (CCR) is now referred to as Luas Network Maintenance Centre (LNMC)

80 The Dewirement Guide has eleven steps. The first two steps, are relevant for the immediate actions to be taken by the Traffic Supervisor and are of particular interest to the RAIU investigation, namely:

- De-energise the relevant section of OCS without delay.
- Prevent further movement of trams into the affected area.

81 The Dewirement Guide is a word document, which does not contain a reference number, author or who issued the document or where the document sits in Transdev's Safety Management System. When the "zone identification list" was requested by the RAIU, the RAIU were informed that Transdev "no longer have a copy" of the list, which was not updated since 2007 (despite a number of changes to the Luas network e.g. expansions). When requested, by the RAIU, how the zones were identified, Transdev responded with "The electrical zones are clearly marked on the SCADA pages and are also marked out on the Automatic Vehicle Location System (AVLS) screens. From SCADA the zone would have been indicated in Green as it would have deenergised, this could also be cross referenced on AVLS screens if required". Examples of the SCADA pages are in Figure 6, an example of the AVLS screen is in Figure 12.

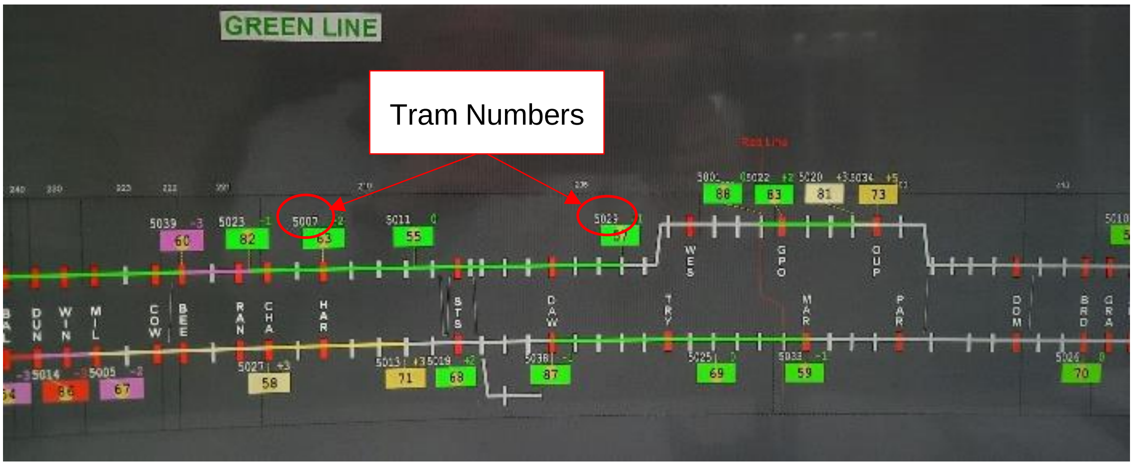

Figure 12 – AVLS Screen shot

Incident Management

82 The Transdev "Incident Management" document (to be referred to as Incident Management Procedure for the remainder of this report), TLDR-S-PR-0013, Rev 01.0, approved on the 25th October 2019, sets out Transdev's response to accidents and incidents by defining roles and procedures to provide an effective and safe response to incidents, accidents and other emergencies which may occur on the Luas system.

83 The Incident Management Procedure is a high level document with the following headings: purpose; scope; introduction; general response to emergencies; the emergency message; media relations; major incident response; additional actions for incidents involving dangerous goods; additional actions in the event of a pollution incident on Luas controlled infrastructure; action in the event of a fatality or serious injury; and, preservation of evidence.

84 Dewirement or OCS incidents are not covered in the document i.e. in events similar to those on the 2nd November 2020. Dewirement is only mentioned in terms of incidents that result in a fatality of serious injury.

85 There is no indication as to where the Incident Management Procedure sits in Transdev's Safety Management System.

Events before, during & after the incident

Events before the incident

86 At 14:31:52 hrs, on the 2nd November 2020, Luas Service 65, operated by Tram 5010, served Stillorgan Stop inbound platform.

87 Having observed passengers entering and exiting tram, Driver 5010 closed the passenger doors and moved forward to Stillorgan inbound tram signal, Signal B11 (Figure 13), at 14:34:27 hrs.

Figure 13 – Signal B11 (photograph taken from end of platform)

88 At approximately 14:34 hrs Tram 5003 departed Central Park for Sandyford (Service 88).

Events during the incident

89 At 14:34:59 hrs the OCS broke while Tram 5010 was stopped at Signal B11 and the MCB on Tram 5010 opened.

90 The broken OCS wire fell on the roof of Tram 5010 resulted in OCS ESS HSCB Sandyford L1 (into City Centre / Inbound) short circuiting, opening and de-energising the section (see Figure 14).

Figure 14 – Short-circuit between the OCS and roof of Tram 5010

91 At 14:35:15 hrs, Driver 5010 reports to the Traffic Supervisor that the OCS was sagging. The Traffic Supervisor views the CCTV monitors for Stillorgan Stop (Figure 15) and sees that the OCS wire has detached.

Figure 15 – Stillorgan CCTV images viewed by Traffic Supervisor

92 The detached OCS wire has one end approximately two meters above the roof of Tram 5010 (Figure 16) and the other end resting on the roof of Tram 5010, the outbound track and the platform at the Stillorgan Stop (Figure 17).

Figure 16 – OCS hanging over Tram 5010

Figure 17 – OCS wire on outbound track

93 As the Stillorgan Stop area was already de-energised, the Traffic Supervisor did not need to de-energise the section. The Traffic Supervisor did not de-energise any other relevant sections of the OCS.

94 At 14:35:50 hrs, the Traffic Supervisor made a General Call, stating "Control to 65, 88, 62, 84, hold you location"; the Traffic Supervisor was referring to the service numbers and requesting them to stop their trams. Service 65 (Tram 5010) was at Stillorgan; Service 88 (Tram 5003) was travelling from Central Park to Sandyford (timetable Carrickmines – Sandyford); Service 62 (Tram 5002) was travelling from Broombridge to Sandyford (timetable Dundrum to Sandyford); Service 84 (Tram 5025) was travelling from Windy Arbour to Dundrum (timetable Beechwood to Dundrum), see Figure 18 for location of trams when the Traffic Supervisor requests that they "hold" (stop). All drivers acknowledge the instructions.

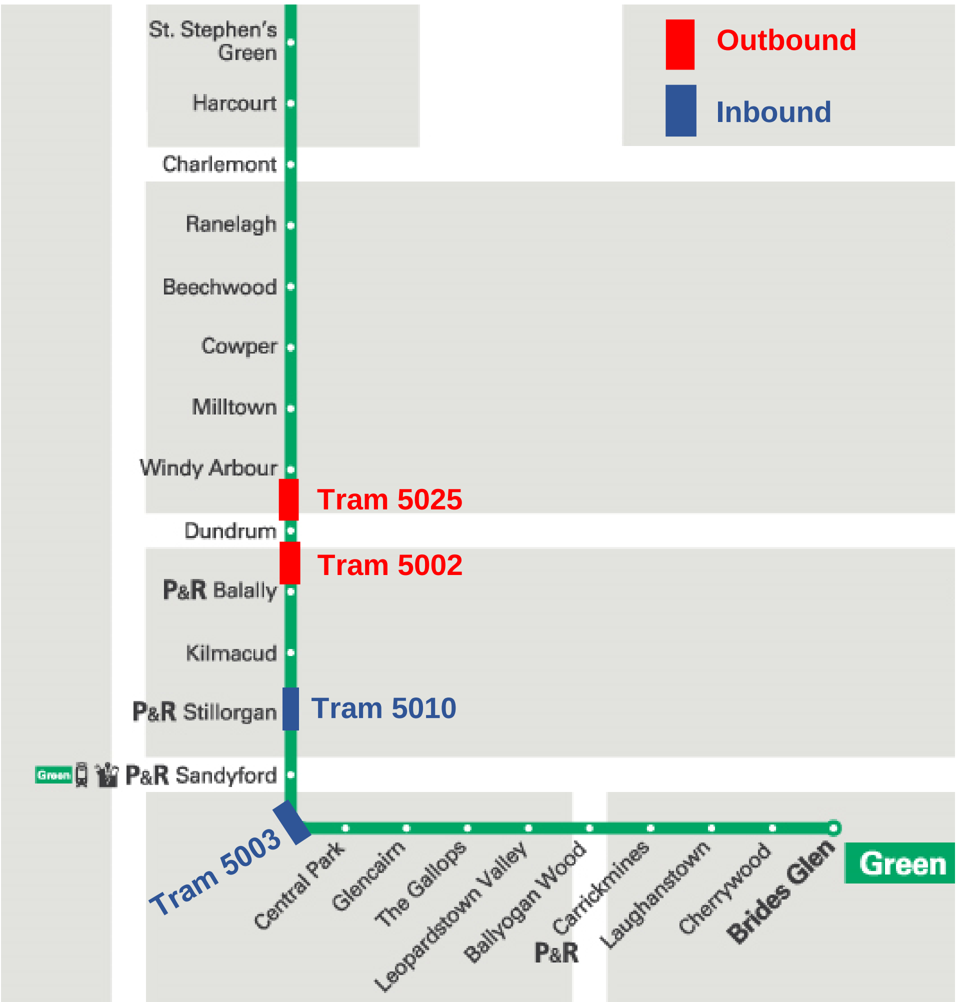

Figure 18 – Location of trams in area of de-energisation

Figure for illustrative purposes only, the green line indicated in double track

95 At 14:35:57 hrs, the Traffic Supervisor contacts Driver 5010 to try and establish what has occurred with the OCS. Driver 5010 states that the OCS "it's definitely not down, but it's hanging a lot", further stating that "it doesn't look right at all".

96 At 14:36:28 hrs, the Traffic Supervisor, thirty-eight seconds after the initial call to stop trams, calls for Service 84 (Tram 5025) to "Hold at Dundrum" i.e. proceed to Dundrum and stop; and for Service 88 (Tram 5003) to "Hold at when you get to Sandyford" i.e. proceed to Sandyford and stop.

97 At this time, Service 88 (Tram 5003) was travelling from Central Park to Sandyford (Figure 19).

98 At approximately 14:37:08 hrs, the Traffic Supervisor instructs Driver 5010 to "detram" i.e. allow passengers off the tram. The Traffic Supervisor further instructs: Service 62 (Tram 5002) to hold where they are; Service 84 (Tram 5025) to travel no further than Balally; Service 88 (Tram 5003) to travel to Sandyford and hold (14:37:22 hrs). The drivers

acknowledge the Traffic Supervisor's instructions. It is noted that Service 62 (Tram 5002) was also in the section).

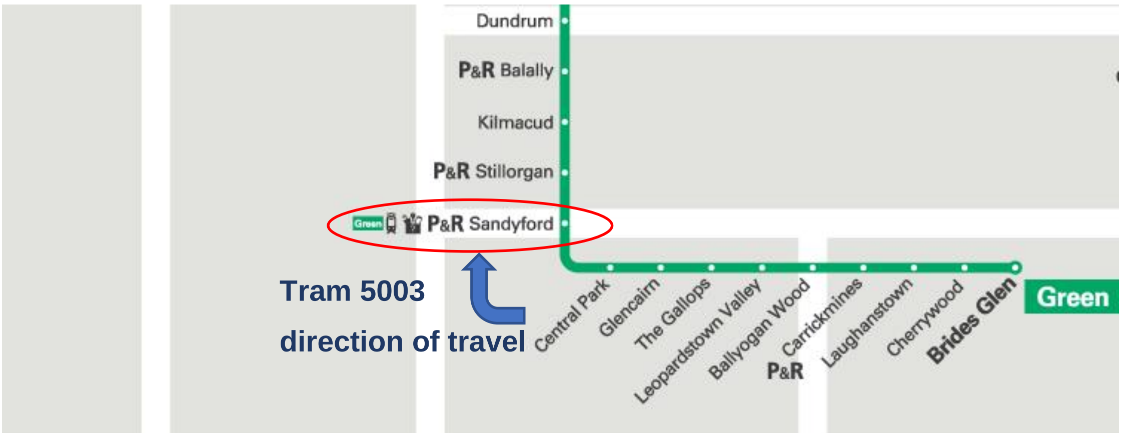

Figure 19 – Location of Tram 5003

Figure for illustrative purposes only, the green line indicated in double track

99 At 14:37:31 hrs, two minutes and thirty-two seconds after the first short circuit, Tram 5003 entered the Insulated Overlap between Sandyford ESS and Central Park (the Insulated Overlap is prior to Sandyford Stop); when the pantograph bridged both sections of wire, the de-energised section at Stillorgan Stop re-energising.

100 With the broken wire still resting against the roof of Tram 5010 at Stillorgan, the re-energising of the section resulted in a second short circuit (Figure 20).

Figure 20 – Second short-circuit between the OCS and roof of Tram 5010

101 Additionally, Sandyford HSCB L2 and Glencairn HSCB L1 tripped out due to overcurrent (Figure 21); this is visible to the Traffic Supervisor, through using SCADA.

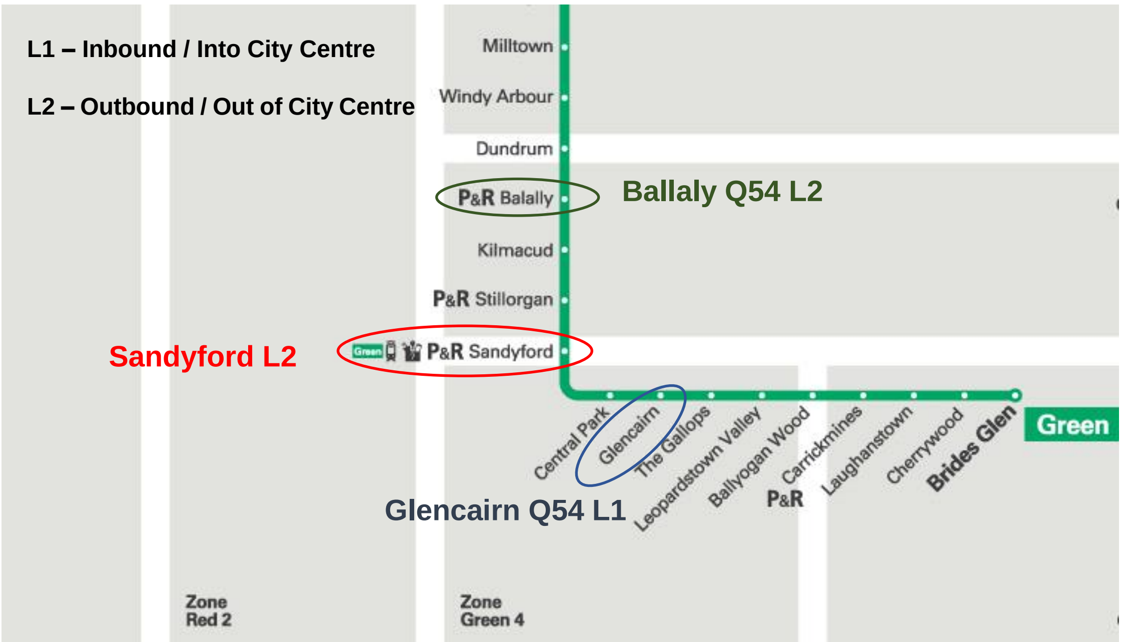

Figure 21 – OCS ESS HSCB Locations

Figure for illustrative purposes only, the green line indicated in double track

102 At 14:37:35 hrs, Driver 5010 contacts the Traffic Supervisor to inform him that there was a "big bang" outside the tram (detramming had not commenced). The Traffic Supervisor advises Driver 5010 to "stand-by" while he checks the position of the pantograph; he sees that the pantograph is down. Driver 5010 states that passengers will remain on the tram.

103 At 14:38:24 hrs, Driver 5003 calls the Traffic Supervisor to tell him that he has no power for the tram.

104 At 14:38:34 hrs, the Traffic Supervisor tells Driver 5010 to keep passengers on the tram; he repeats this again at 14:38:56 hrs.

105 At 14:39:26 hrs the driver of Service 84 (Tram 5025) informs the Traffic Supervisor that he has lost power at Balally. The Traffic Supervisor, requests that the driver hold at Balally and to detram the passengers; he also requests that he drop the pantograph.

106 Between 14:39 and 14:00 hrs, the Traffic Supervisor makes some requests for drivers to hold and detram.

Events after the incident

107 Between 14:41 hrs and 14:48 hrs, the Traffic Supervisor contacted An Garda Síochána, Dublin City Council, Transdev On-call Officer, and the VMC.

108 LNMC reported to the S2M (Joint Venture Systems Maintenance Team) that there was an issue with the OHLE at Stillorgan Stop and that the section is de-energised and requests their attendance on site.

109 An Garda Síochána arrived on-site at 15:00 hrs and cordoned off the incident site.

110 At 15:12 hrs, S2M arrive on site.

111 At 15:20 hrs, S2M put on an emergency isolation to facilitate passenger de-tramming.

112 At 15:50 hrs, passengers of Service 65 (Tram 5010) are de-trammed at Stillorgan Stop.

113 At 16:50 hrs, full isolation of Glencairn – Sandyford – Ballaly put in place, and OCS maintenance staff replaced twenty-nine meters of contact wire. Parafil cross spans on both sides of the wire break were also replaced.

114 Post-incident, the carbon bands on all tram pantographs operating on the Green Line were checked for damage.

115 Trams operated on the south side of the failure from Brides Glen to the Gallops and on the north side from Broombridge to Beechwood for approximately eight hours while the OCS was being repaired.

116 Full service was restored at 21:15 hrs.

Similar Occurrences

117 The RAIU are aware of one similar occurrence, which occurred on the 3rd February 2015, when the OCS failed on the outbound Green Line. The incident occurred after Tram 5008 served the Milltown Stop resulting in the contact wire breaking; earlier that day there had been reports of sparking from pantographs on a number of trams.

118 Alstom Ireland Limited, the IMC in 2015, investigated and published a report (on the 2nd October 2015) on the incident, entitled "OCS Dewirement at Milltown Outbound". The investigation report concluded that the immediate cause of the contact wire failing whilst Tram 5008 was stationary at Milltown was at the point where the contact wire was in contact with the pantograph carbon band. The basic cause was that the temperature of the contact wire was elevated locally at the point it was in contact with the pantograph carbon band, which annealed the copper wire, reducing its mechanical strength; as a result, the normal tension in the contact wire was sufficient to cause its failure.

119 The root causes were identified as:

- Infrastructure defects at Sandyford /Stillorgan and /or Carrickmines resulted in chips to the pantograph carbon bands. During service, as the contact wire traversed across the carbon band it became trapped in the chip, which led to a groove in the carbon band. The groove then grew exponentially as the larger the groove, the longer the contact wire was trapped in it;
- When Tram 5008 arrived at Milltown the contact wire was sitting in the groove, reducing the contact patch between the wire and the carbon band. It is also possible that the contact wire was sitting in the groove on the front carbon band, but not on the rear, tilting the pantograph head and further reducing the contact patch;
- This reduced contact patch significantly and increased the electrically resistance resulting in the localised heating of the contact wire and its subsequent failure.

120 Although the report contained a photograph of the failed OCS wire from Milltown (Figure 22), the report did not comment on the black coating visible on the wire.

Figure 22 – Failed OCS wire from Milltown

Analysis

Luas Pantographs

121 The pantograph is an articulated, mechanical assembly that facilitates the pickup of current in the OCS wire. Pantographs are maintained by Transdev at intervals of 15,000 km, 60,000 km and 600,000 km (paragraph 52). Tram 5010 received its last maintenance intervention prior to the incident on the 14th October 2020; no faults were reported against the pantograph (paragraph 53).

122 The pantograph of Tram 5010 was inspected post-incident and no faults were found (paragraph 55). The pantograph lowered and raised smoothly, the uplift pressures were within the set parameters, and, the carbon bands were adequate (paragraph 56).

123 In terms of other Green Line pantographs, all thirty-two trams, had the pantograph carbon bands checked post incident, with two trams (Tram 5019 and Tram 5024) requiring the carbon bands to be replaced (paragraph 57).

Luas OCS

Energising/De-energising/Isolation

124 Trams are powered by an OCS providing 750V DC delivered from twenty ESSs (paragraph 59).

125 The OCS is sectioned electrically to allow maintenance intervention including planned and emergency repair of the OCS without the need to de-energise the complete line; insulated overlaps are used to provide a continuous supply of power to the tram when the tram passes from one section to the next and also allows for de-energising of one section at a time (there is no possibility of the two sections coming into contact with each other except when bridged by a pantograph); one of these insulated overlaps is between Sandyford ESS and Central Park (paragraph 61).

126 SCADA displays information on a screen in the LNMC, which allows the operator to see the part of the Luas network that is energised, de-energised as well as equipment in failure mode. Commands can be sent to isolate one or more sub-stations or sections of a line (paragraph 65). The SCADA printout for the day of the incident, illustrates the trip out of L1 Sandyford substation and intertrip of Balally (as a result of the OCS wire parting and short circuiting against the roof of Tram 5010); and, Tram 5003 entering the Insulated Overlap between Sandyford and Central Park resulting in the re-energising of the L2 Sandyford and Balally section, which resulted in a second short circuit, as the OCS was still resting on the roof of Tram 5010 (paragraph 66).

OCS Wire

Mechanism of failure

127 The S2M Report identifies the immediate cause as the parting of the overhead caused by the high electric current flowing from the wire to the tram's pantograph, through the failure mode of necking caused by Joule heat due to the current flowing between the contact wire and the pantograph carbon band, through an arc due to poor contact conditions, reasons for which are not given (paragraph 72).

128 The ms4i Report identifies the black coating over the failed section of OCS as Cupric Oxide which forms on copper when it is heated to between 300°C and 400°C and cooled and resulted in the annealing of the wire; negating the effects of cold drawing, resulting in a reduction in the tensile strength of the wire i.e. failure due to ductile overloading. In addition, Cupric Oxide is electrically insulative, which results in a poor connection between the pantograph and the OCS wire, which subsequently increases the temperature when the current flows, particularly when the tram was starting off from the platform or signal (paragraphs 76 to 79).

129 It is also noted, in a similar occurrence in 2015 at Milltown Stop, Cupric Oxide also appears to have been present (paragraph 120, Figure 22); indicating overheating.

Inspections

130 OCS inspections are carried out every three months, six months and two years.

131 The Stillorgan section received its last inspection between 5th October and the 1st November 2020 (combined three and six monthly (paragraph 63)) with no reports of necking (paragraph 63), with the incident occurring on the 2nd November i.e. within one month. However, post-incident, two-locations (15 m and 30 m from the tram stop line) displayed necking (paragraph 70).

132 In addition, eight other locations on the Green Line displayed signs of necking (paragraph 68), totalling ten locations, when including the two necking locations at Stillorgan. It should be noted that three stops displayed multiple locations of necking i.e. two locations at Stillorgan, two at Windy Arbour and three at Sandyford. The total of ten necking locations, and multiple necking sites at stops indicates that the OCS inspection regime is not adequate for the early detection of necking.

Dewirement and incident management

Dewirement Guide

133 Transdev's Dewirement Guide is a one page document, consisting of eleven steps, to assist Traffic Supervisors in the event of OCS dewirement (paragraph 79). The steps include: the de-energisation of the OCS without delay; and, prevention of movement of trams in the affected area (Figure 11). The "zone identification list" no longer exists and in its place, the Traffic Supervisors have adopted, a non-formalised procedure, of using the SCADA screens to determine what sections to de-energise (paragraph 81).

Incident Management Procedure

134 The Incident Management Procedure is a high level document, which primarily deals with major incidents and accidents i.e. fatalities or serious injuries (paragraphs 82 - 83); as a result, there is no guidance in relation to incidents such as dewirements (paragraph 84).

Actions of the Traffic Supervisor

135 Transdev's Dewirement Guide and Incident Management Procedure were available to the Traffic Supervisor. In terms of the Incident Management Procedure, there was no information of use to the Traffic Supervisor for the dewirement incident (paragraph 134).

136 The Traffic Supervisor was not required to de-energise the OCS section at Stillorgan as the section de-energised when the broken OCS short-circuited when it hit the roof of Tram 5010 (paragraph 90), as he could see that this was de-energised on SCADA. In relation to the other actions taken by the Traffic Supervisor on the day of the incident, as compared to the Dewirement Guide (Figure 11), the Traffic Supervisor:

- Initially prevented further movement of trams into the affected area by issuing a "hold your location" request to trams in the affected (paragraph 93). However, this action was rescinded when he allowed trams to continue to their next Stops in an effort to reform services around the affected section (paragraph 95). This included Service 88 (Tram 5003), which the Traffic Supervisor allowed to continue to Sandyford, which in turn bridged the Insulated Overlap between Sandyford ESS and Central Park, resulting in the re-energised of the section at Stillorgan Stop (paragraph 98);
- Arranged the attendance of An Garda Síochána (paragraph 107), the IMC S2M (paragraph 106), the On-Call officer and the VMC (paragraph 107);

- After the second short-circuit, ensure the safety of staff and passengers, by holding them on the tram, until an emergency isolation was carried out by the IMC (paragraph 109).

Conclusions

Luas Pantograph

137 There were no faults found with the pantograph during its last maintenance intervention on the 14th October 2020; and no faults were detected post-incident (paragraphs 121 - 122); and as a result the condition of the pantograph was not contributory to the incident. However, it is noted that two other trams (of a total of thirty-two) on the Green Line required the carbon bands to be replaced, accounting for 6% of trams (paragraph 123).

Luas OCS

OCS Wire Inspections

138 OCS wire inspections are carried out at a frequency of three months, six months and every two years (paragraph 130). At the time of the incident, Stillorgan had received its scheduled inspection in the month prior to the incident (paragraph 131).

139 At the time of the incident, the Green Line was in date for scheduled OCS inspections with no reports of necking present, but a post incident high level inspections of the Green Line revealed necking present at eight locations, with multiple necking identified at three stops (paragraph 132). This indicates that the inspection regime is not robust in terms of identifying necking.

OCS Mechanism of Failure

140 The S2M Report and ms4i Report both identify wire necking due to heat as the cause of the failure (paragraph 127 - 128).

141 In addition, the ms4i Report identifies the presence of Cupric Oxide on the OCS wire, present as a result of over-heating due to high temperatures (between 300°C and 400°C); these raised temperatures and subsequent cooling negated the effect of cold drawing performed at manufacture and resulted in the wire failing through tensile loading despite it been within normal operating parameters (paragraph 128). The occurrence of over-heating, due to the presence of Cupric Oxide was present in a similar occurrence at Milltown in 2015; however, Alstom Ireland Limited did not link its presence to over-heating (paragraph 129).

Dewirement and incident management

142 Transdev's Dewirement Guide instructs Traffic Supervisors to de-energise the relevant sections of OCS without delay prevention of movement of trams in the affected area. However, the "zone identification list" no longer exists; and no clear formal instructs have been created in relation to which zones to isolate (paragraph 133).

143 Transdev's Incident Management Procedure does not deal with OCS dewirement, where there are no fatalities or injuries (paragraph 134) and as such was not of use to the Traffic Supervisor in this incident.

144 The Traffic Supervisor did take a number of actions of the day of the incident, namely that the Traffic Supervisor:

- Checked SCADA to see that the Stillorgan Section was de-energised;
- Initially stopped all trams at their locations, by issuing a "hold you location" request to those trams;
- Arranged for the relevant parties to attend site (paragraph 136).

145 However, the incident (re-energising) occurred as a result of the Traffic Supervisor not holding the other trams at their locations until an emergency isolation was placed at the Stillorgan section (paragraph 136).

146 These actions allowed Service 88 (Tram 5003) to continue to Sandyford; this tram then bridged the Insulated Overlap between Sandyford ESS and Central Park, which resulted in the re-energising of the section at Stillorgan Stop (paragraph 136), approximately two and a half minutes after the initial call to the Traffic Supervisor.

Causal, contributing and systemic factors

147 In this incident, there are two distinct events, namely the failure of the OCS wire and the re-energisation of the failed OCS wire, and as such the causal, contributing and systemic factors are separated.

148 In terms of the OCS mechanism of failure, the OCS wire failed for the following causal factors:

- CaF-01 - The OCS wire at Stillorgan suffered from necking (reducing its tensile strength) as a result of the OCS wire becoming annealed due to over-heating;
- CaF-02 – The planned inspections of the OCS did not identify the presence of necking at the Stillorgan Stop.

149 Contributory factors include:

- CoF-01 – The inspections of the OCS did not identify the presence of Cupric Oxide as a precursor to the necking, either at Stillorgan in 2020 or at Milltown in 2015;
- CoF-02 – The stopping position of trams, consistently in the same location (15 m or 30 m from the Stop Line) resulted in the pantograph drawing down the current at the same location on the OCS wire.

150 A systemic factor was identified as:

- SF-01 – The OCS inspection regime was not robust and failed to identify OCS wire necking, as evidenced at numerous locations on the Green Line.

151 The re-energisation of the broken OCS Wire at Stillorgan was as a result of:

- CaF-03 – Service 88 (Tram 5003), although initially stopped by the Traffic Supervisor, was permitted to continue to Sandyford Stop; while travelling to Sandyford, the pantograph of Tram 5003 bridged the Insulated Overlap between Sandyford ESS and Central Park.

152 There are no contributing factors associated with this incident.

153 Systemic factors:

- SF-02 – The Dewirement Guide did not provide enough details for the Traffic Supervisor to manage a dewirement incident appropriately;
- SF-03 – The Incident Management Procedure only provides information for larger incidents, and as such did not provide information in relation to dewirements incidents where there are no fatalities or injuries.

Additional observations

154 Although not causal, contributing, or systemic, the RAIU make the following additional observations:

- AO-01 – The OTDR raw data for the incident was not downloaded post incident and subsequently overwritten and not available for analysis;
- AO-02 – The electrical resistance of the vehicle earth bonding is not required to be measured;
- AO-03 – Cupric Oxide was present in this incident and the Milltown incident in 2015. Although known as a precursor to necking, the reason for the presence of Cupric Oxide was not determined in this investigation.

Measures taken by Transdev since the incident

OCS inspection

155 Post incident S2M conducted a full Green Line high level OCS inspection checking for contact wire necking and pantograph impact marks. Necking was identified at three locations at Sandyford two locations at Windy Arbour and one each at Glencairn, Milltown and Cowper Stops.

156 In relation to future OCS inspections, S2M produced a power point presentation for its staff to inform them of how to identify OCS necking and the steps to be followed when necking is found. The presentation included the following:

- Contact wire necking is caused by Joule heat due to the current flowing between the contact wire and the contact strip, due to poor contact conditions;
- Once the contact wire is softened, its mechanical strength decreases resulting in breakage due to tension force;
- Contact wire necking is more frequently found in areas where the tram accelerates i.e. leaving tram stops or crossing road junctions.
- Necking may present as the narrowing of the cross section of the contact wire over a very short distance <20mm. Presence of a burn mark or dark ring around the contact wire at the point of narrowing.
- The location where necking was identified during the full heigh level inspection were either at approximately 15 m or 30 m mark from the tram stop line, this corresponds with the location where the tram stops, and the pantographs makes contact with the OCS wire for a duration of time before it accelerates;
- Where necking is found, inspection staff must: take a photograph and record the location; measure the wire at its narrowest point and record the height and stagger; fit a contact wire joiner across the damaged point to prevent the wire from pulling apart;
- The presentation also includes updated Tool Box Talks and Method Statements, with visual aids, likely location of necking and corrective actions to the taken to aid in the identification of necking;
- However, the presentation did not reference the likelihood of a black coating of Cupric Oxide on the OCS as a result of high temperature oxidation.

157 In terms of the OCS Wire, an independent laboratory has been commissioned to carry out both non-destructive testing and tensile strength tests on samples of OCS Contact Wire; the scope of the testing is to detect potential failures in advance.

Pantograph inspections

158 All trams operating on the Green Line had the pantograph carbon bands checked post-incident. Of the thirty-two trams checked two trams, Trams 5019 and Tram 5024, required the carbon bands to be replaced; this accounts for 6% of the trams.

159 An inspection of trams operating post-incident identified the pantograph on Tram 5019 sparking. Tram 5019 was tow pushed back to the depot for inspection. The pantograph pressure was recorded as within tolerance. The carbon bands were replaced and rechecked after one day running with no fault found.

OCS and Pantograph Interface

160 Transdev have proposed to commission a study into the impact of longer trams, congestion of trams in electrical section and the interface of the OCS with the pantographs.

Dewirement Guide

161 Transdev are in the process of re-developing a "zone identification list" to be attached to the Dewirement Guide. The Dewirement Guide is now incorporated into the LNMC Manual and is awaiting issue to the Traffic Supervisors.

Post-incident evidence management

162 A post-incident check sheet has been developed to ensure that OTDR, CCTV, etc, has been collected after an emergency incident.

Safety Recommendations

Introduction to safety recommendation

163 In accordance with the European Union (Railway Safety) (Reporting and Investigation of Serious Accidents, Accidents and Incidents) Regulations 2020), recommendations are addressed to the national safety authority, the CRR. The recommendation is directed to the party identified in each recommendation.

Absence of safety recommendations due to measures already taken

164 No measures have been taken that would remove the need for safety recommendations in this investigation.

Safety recommendations as a result of this incident

165 In terms of the OCS mechanism of failure, the OCS wire failed as a result of necking, which was not detected in scheduled OCS inspections. In addition, post-incident inspections of the Green Line indicate necking at eight other locations of the Green Line. Also, the current inspection regime does not identify Cupric Oxide as a precursor to necking. As a result, the RAIU make the following safety recommendation (CaF-01, CaF-02, CoF-01, CoF-02, SF-01):

Safety Recommendation 202106-01

Transdev, along with S2M, should conduct a full review of their inspection processes for OCS wires to ensure pre-cursors, likely location and faults with the OCS are referenced.

166 In terms of the re-energisation of the OCS wire, after initial failure of the OCS, the Traffic Supervisor permitted trams to travel in the area of the de-energised tram (Tram 5010 at Stillorgan); which resulted in Tram 5003 travelling to Sandyford, with the pantograph of Tram 5003 bridging the Insulated Overlap between Sandyford ESS and Central Park. It appears that the current suite of documents in relation to dewirement/incident management (i.e. Dewirement Guide and Incident Management Procedure) fail to address the events of the day of the incident. As a result, the RAIU make the following safety recommendation (CaF-03, CaF-04):

Safety Recommendation 202106-02

Transdev should conduct a full review and update of their dewirement/incident management documents, to ensure that dewirement incidents are fully addressed; in particular in relation to zone identification for de-energised sections of track in the event of an incident. These documents should then be fully briefed to the Traffic Supervisors.

Safety recommendations as a result of additional observations

167 Although noted as not being a contributory factor in the failure of the OCS wire, the tram OTDR was not downloaded post incident and as a result the raw data was overwritten and not available for analysis. As a result, the RAIU make the following safety recommendation:

Safety Recommendation 202106-03

Transdev should put a process in place that all trams involved in serious incidents have the OTDR downloaded as soon as possible to prevent overwriting of the data.

168 Although noted as not being a contributory factor in the failure of the OCS wire, it was noted that vehicle planned maintenance did not require the earth bonding to be measured, the RAIU make the following safety recommendation:

Safety Recommendation 202106-04

Transdev should include the electrical resistance measuring of vehicle earth bonding in the planned preventative maintenance regime for all trams.

169 The reason for the presence of Cupric Oxide could not be determined during this investigation; as such, the RAIU make the following safety recommendation:

<u>Safety Recommendation 202106-05</u>

Transdev should investigate the reason for the build-up of Cupric Oxide on the OCS wire. The investigation should include but not limited to:

- **Impact of longer trams, and congestion of trams in electrical sections;**
- **Electrical resistance monitoring of tram to identify if high current demand is an issue;**
- **Consequence of trams working in degraded mode on current demand;**
- **The pantograph carbon bands and OCS interface.**

Additional Information

List of abbreviations

AC	Alternating Current
AMP	Annual Maintenance Plan
AVLS	Automatic Vehicle Location System
CCR	Central Control Room now known as Luas Network Management Centre (LNMC)
CCTV	Close Circuit Television
CI	Chief Investigator
DC	Direct Current
DOT	Department Of Transport
ESS	Electrical Sub Station
hr	hour
HSCB	High Speed Circuit Breaker
km	kilometre
L1	Trams travelling on the Green Line in the direction to the city centre.
L2	Trams travelling on the Green Line in the direction out of the city centre.
LNMC	Luas Network Management Centre previously known as Central Control Room (CCR)
LRV	Light Rail Vehicle
m	metre
OCS	Overhead Contact System
OTDR	On Tram Data Recorder
RAIU	Railway Accident Investigation Unit
RFI	Request For Information
S2M	Joint Venture Systems Maintenance Team
SCADA	Supervisory Control And Data Acquisition
TED	Traffic Event Database
TSI	Tramway Safety Instruction
VMC	Vehicle Maintenance Contractor

Glossary of terms

Accident	An unwanted or unintended sudden event or a specific chain of such events which have harmful consequences. For heavy rail, the EU Agency for Railways divides accidents into the following categories: collisions, derailments, level-crossing accidents, accidents to persons caused by rolling stock in motion, fires and others.
Alternating current	Alternating current (AC) is an electric current which periodically reverses direction and changes its magnitude continuously with time in contrast to direct current (DC) which flows only in one direction.
Annealing	A heath treatment process which alters the microstructure of a material to change its mechanical or electrical properties; resulting in reducing hardness and increase ductility.
Article 20 of Directive (EU) 2016/798, Obligation to investigation	Article 20 (1) Member States shall ensure that an investigation is carried out by the investigating body referred to in Article 22 after any serious accident on the Union rail system. The objective of the investigation shall be to improve, where possible, railway safety and the prevention of accidents. Article 20 (2) The investigating body referred to in Article 22 may also investigate those accidents and incidents which under slightly different conditions might have led to serious accidents, including technical failures of the structural subsystems or of interoperability constituents of the Union rail system. The investigating body may decide whether or not an investigation of such an accident or incident is to be undertaken. In making its decision it shall take into account: (a) the seriousness of the accident or incident; (b) whether it forms part of a series of accidents or incidents relevant to the system as a whole; (c) its impact on railway safety; and (d) requests from infrastructure managers, railway undertakings, the national safety authority or the Member States.
Causal Factor	Any action, omission, event or condition, or a combination thereof that if corrected, eliminated, or avoided would have prevented the occurrence, in all likelihood.

Central Control Room	Location from which tram operations are managed and monitored now known as Luas Network Management Centre.
Circuit Breaker	A switch arranged to open automatically when a current above a predetermined value flows through it.
Cold Drawing (manufacturing)	A metalworking process that uses tensile forces to stretch (elongate) metal, glass, or plastic. As the metal is drawn (pulled), it stretches to become thinner, to achieve a desired shape and thickness. For wire, bar, and tube drawing, the starting stock is drawn through a die to reduce its diameter and increase its length. Drawing is usually performed at room temperature, thus classified a cold working process.
Conductor	A body or substance which permits the flow of electricity.
Contributing Factor	Any action, omission, event or condition that affects an occurrence by increasing its likelihood, accelerating the effect in time or increasing the severity of the consequences, but the elimination of which would not have prevented the occurrence.
De-energised	The remote switching undertaken by the Traffic Supervisor through the SCADA system to remove the traction power supply feeding the OCS.
Direct Current	Direct current (DC) is one-directional flow of electric charge. Direct current may be converted into alternating current (AC) via an inverter.
Earth	The potential of the general mass of the earth and of any conductor in direct electrical connection with it. Note: "Earth" for the purpose of overhead line equipment only, is the general mass of earth not directly connected to the traction return circuit.
Electrical Sub-Station	Supplying 750 V DC to the trams.
High Speed Circuit Breaker	A switch in an electric circuit which is usually remotely controlled and will open automatically should an excessive current pass through it.
Incident	Any occurrence, other than an accident or serious accident, associated with the operation of trains and affecting the safety of operation. For heavy rail, the EU Agency for Railways divides incidents into the following categories: infrastructure; energy; control-command & signalling; rolling stock; traffic operations & management and others.

Insulated Overlap	Designed to maintain the continuity of the passage of the pantograph without the loss of performance, under all temperature and operating conditions. The separation between conductors is such that, in the event of an isolation at one of the sections, there shall be no possibility of the two sections coming into contact with each other except when bridged by a pantograph. In normal operating conditions there should be no arc drawn by the pantograph when the two sections are bridged.
Insulator	Material which offers extremely high resistance to the passage of electricity.
Investigation	A process conducted for the purpose of accident and incident prevention which includes the gathering and analysis of information, the drawing of conclusions, including the determination of causes and, when appropriate, the making of safety recommendations
Isolated	Electrical equipment is said to be isolated when it is disconnected from any source of electricity supply.
Joule heating	The process by which the passage of an electric current through a conductor produces heat.
Luas Network Management Centre	Luas Network Management Centre Location from which tram operations are managed and monitored previously known as Central Control Room.
Necking	A decrease in cross section area of the Overhead Contact System wire due to tensile deformation.
Pantograph	A collapsible frame mounted on insulators on the roof of electric motor cars which bears against the contact wire and through which the electrical current is collected from the overhead line equipment.
Carbon band	This is a long-extruded carbon fitted into an aluminium carrier that is provided on top of the pantograph and collects current from an overhead wire. This is the point of interface between the tram and the OCS.
Serious Accident	Any train collision or derailment of trains, resulting in the death of at least one person or serious injuries to five or more persons or extensive damage to rolling stock, the infrastructure or the environment, and any other similar accident with an obvious impact on railway safety

	regulation or the management of safety. For heavy rail, the EU Agency for Railways divides serious accidents into the following categories: collisions, derailments, level-crossing accidents, accidents to persons caused by rolling stock in motion, fires and others.
Substation	A building that contains electrical equipment including transformers and high-speed circuit breakers and supplies electrical power to the OCS. There are 10 substations on the red line and 12 on the green line. The power to the substations is supplied from the national grid at 10.5Kv AC, this is converted to 750v DC, which is supplied to the trams via the OCS.
Supervisory Control And Data Acquisition	Used to remotely monitor and control all the power supply equipment of the Luas network. Information displayed on screen allows the operator to see which part of the Luas is energised or not, also equipment in failure mode. Commands can be sent to isolate one or more substations or a section of a line. All information relevant to the substations, i.e. fire alarm, intrusion is also reported on these screens. The status of the power is also represented by colour coding. Green: De-energised, Red: Energised, Yellow: Inconsistent status (unknown), Orange/Pink: Identifies a fault
Systemic Factor	Any causal or contributing factor of an organisational, managerial, societal or regulatory nature that is likely to affect similar and related occurrences in the future, including, in particular the regulatory framework conditions, the design and application of the safety management system, skills of the staff, procedures and maintenance.
Traffic Event Database	A repository for everything that occurs on or near the network during an operational shift is recorded. All incident details must be recorded in Traffic Event Database with each incident detail recorded chronologically.

References

ms4i (2021), Contact wire from the overhead line equipment of Dublin's Luas tram system failure analysis report.

S2M (2020), Contact wire necking power point presentation S2M.

S2M (2020), Overhead line failure at Stillorgan tram stop 02/11/20 report.

Transdev (2007), CCR Procedure Dewirement Quick ref guide", Rev A.

Transdev (2019), Incident Management, Rev 01.0, Document ID Code: TDLR-S-PR-0013. Alstom Ireland Limited (2015),

PST 14981 OCS Dewirement at Milltown Outbound Final Report Alstom 02/10/2015.

Transdev (2019), Luas Network Management Centre Manual, TDLR-OP-M, Issue 1, 6/11/2019.

Transdev (2015), TDLR-LUAS-WI-00652, Issue E, Check of upward contact force of the bow on the of the catenary.