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*Research Article*

# Failure Mode Analysis and Maintenance of Railway Overhead Line Rigid Stainless Steel Droppers and Multi-Strand Copper Jumpers

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Droppers and jumpers are important components of railway overhead line electrification. Their effective maintenance is critical for the railway's safe and reliable operation; the consequences of their failure can be disproportionally serious. This paper systematically analyses the components' failure by applying the method of failure modes and effects analysis to the maintenance records and incident statistics of Britain's East Coast Main Line. The analysis is presented with photographic evidence and a review of the current maintenance strategy and practice that addresses the risk of failure. These results can support improved dropper and jumper design and the development of more effective maintenance strategies to further prevent failure and operational disruption.

## 1. Introduction

Running pantographs must maintain constant contact with the overhead line contact wire, so electricity can be supplied to trains without interruption. This requires the contact systems to have high stiffness, few hard spots, and freedom from resonance in the range of normal operating speed [1]. Important factors in high stiffness include (a) the contact system's geometry—maintaining a uniform wire height as much as possible [2]; (b) the type of the contact system, e.g., simple, stitched, and compound; and (c) its droppers' material, manufacture and spacing.

Britain's East Coast Main Line (ECML) between Cambridge Junction and Marshall Meadows primarily adopts a simple-structure overhead line contact system with rigid stainless steel droppers and flexible multi-strand copper jumpers for its maximum 125 mph line speed operation. The droppers take the weight of the contact wire and hold it at its designed vertical position, while the jumpers are mainly for conducting the electricity or electrical potential equalising. Droppers can fail very often; on average, four dropper failures were reported every week in 2020, and this number decreased to three in 2021 on the ECML between Cambridge Junction and Stoke Junction. The impact of a single failure can be minor to very significant. In total, the dropper failures caused 2,297 min delay in 2020 and 6,472 min delay in 2021. Although, compared to droppers, jumper failures very rarely disrupt train services, in the summer of 2019, a single jumper failure caused 8,133 min delay.

Maintaining the droppers and jumpers effectively is of great importance, and a challenge, to provide each passenger with a safe and reliable journey. A common objective of maintenance is to reduce the per-unit-time operating expense and the loss-of-service cost. The overhead line's high-voltage energisation and the railway's high-speed operation may not give engineers a sufficient opportunity to monitor and investigate the droppers' and jumpers' dynamic performance and failures. Most of the maintenance is performed predominately based on the contact system's static measurements. Since the introduction of frequent 125 mph double pantographs running on the ECML in 2019, the vibration of the overhead line and its subsequent disturbance has become stronger and more impactful. In addition, although a dropper can be renewed in 10 min and a jumper can be renewed in 30 min with staff in a mobile elevated working platform (MEWP), it can take an hour for the staff to set up a safe system of work at the beginning and another hour to cancel it at the end. This makes maintenance costly, time-consuming, and disruptive. As a result, gathering failure information, understanding failure, and proposing more effective maintenance are of great importance and urgency in improving the railway service availability.

This paper focuses on dropper and jumper failure analysis and related maintenance. It applies failure modes and effects analysis (FMEA) as a systematic approach for understanding the failure modes of the droppers and jumpers on the EMCL and presents theoretically sound, data-driven, and experience-based maintenance strategies. The maintenance of railway overhead line electrification has two primary categories—corrective repair and scheduled prevention, and it is briefly reviewed in Section 2 with reference to related literature and research concerning FMEA and failure deterioration. Section 3 introduces dropper and jumper basics, design, and installation in detail. Sections 4 and 5 present their failure modes, effects, rate of occurrence, disruption to train services, and deterioration. Section 6 discusses five effective and practical maintenance strategies for droppers and jumpers to refine maintenance performance and improve railway operation. Finally, research and potential future works are summarised in Section 7.

This paper's analysis and presentation are mainly based on the 2018–2021 operation and maintenance record of the area between Cambridge Junction and Stoke Junction on the ECML. Pictures in this paper are for demonstration purposes.

## 2. Related Work

*2.1. Railway Overhead Line Equipment Maintenance.* The two main categories of maintenance are corrective and preventive [3], and both can be reactive or proactive. Corrective maintenance is sometimes called repair. Its effectiveness relies largely on the early identification of failure and engineers' readiness to respond rapidly. To improve readiness, engineers may prepare standby equipment as a redundancy measure, explore resource diversity, pre-plan maintenance windows (a gap in train services, e.g., 2–6 hr, in which maintenance can be carried out [10]), etc. However, as more processes are put in place, costs generally increase. Preventive maintenance has been mainly schedule-based for decades. A typical and widespread example is the routine check of vulnerable components. Various checks are often nested in a hierarchy of their complexity, such as monthly minor inspections, quarterly tests, and annual overhauls [4]. Routine checking and repair constitute many companies' maintenance practices [5–7].

Schedule-based maintenance improves the railway overhead line equipment's availability, and helps engineers and train operators to develop a determinate business plan [8]. Track access and overhead line isolation for maintenance are agreed in advance, so trains can be planned around maintenance windows [4, 9, 10]. There are three major shortcomings to this strategy. First, the allocation of the engineers' valuable and limited maintenance resources is inflexible in the short term, as there is a fixed schedule to be compliant with. Second, the risk of a missed maintenance activity is assessed generally based on (the trending of) historical maintenance records. Third, when a failure is identified in a routine check, the repair's timescale is difficult to establish accurately without knowing when the failure occurred.

Figure 1: Broken dropper wire that could affect pantograph operation.

Outstanding corrective and preventive maintenance both require condition monitoring and dynamic risk assessment [11]. The monitoring used to be, and is still commonly, achieved by placing a watch person at a high-risk location so that any failed equipment will be reported immediately, with mitigation being implemented promptly. Recent advanced sensing technologies and the development of the Internet of Things make remote, labour-free, continuous, and detailed monitoring increasingly cost-efficient, and maintenance records can be stored electronically and accurately for failure investigation and risk analyses [12, 13]. In recent years, published solutions have included fitting sensors to railway overhead line equipment and remotely monitoring overhead line leaning stanchions [14], tension [15, 16], temperature [17], vibration [18], and neutral sections [19]. Because of the droppers' and jumpers' small size, substantial quantity, and wide distribution, infrastructure-borne monitoring solutions are likely to incur extremely high capital expenditures and operating expenses. More likely, train-borne cameras and advanced image processing techniques (e.g., [20–23]) will be the approach to monitoring dropper and jumper failures and their deterioration. This monitoring is discontinuous—and sometimes too late, as after a fast-running train identifies a service-affecting failure, the train is very unlikely to have a sufficient response time. Figure 1 shows a typical example of a broken dropper being captured by a fast-running train's pantograph camera. The train could not slow down sufficiently at such short notice to reduce the risk of the pantograph being hit by the broken dropper wire.

High-resolution remote condition monitoring provides more comprehensive, accurate, detailed, and continuous decision data for engineers; this enables evolution towards risk-based maintenance planning. Engineers will analyse maintenance records to model the scenarios in which failure is likely to occur, plan ad hoc or enhanced inspections, and deploy their resources more effectively. Repairs will be carried out perfectly (as good as new), minimally (as bad as old), or imperfectly (in between the two extremes) to achieve a better balance between cost and reliability [24]. Failure prevention evolves from a fixed routine towards a more accurate linking of resources to the opportunity for reliability improvement [25].

*2.2. Failure Modes and Effects Analysis.* FMEA is a systematic approach to the identification of failure modes and their causes, the assessment of their impact on system performance, and the understanding of how to detect and prevent failure. Carrying out FMEA helps railway engineers to identify key components, understand the impact of their potential failure on the railway's operation, and plan suitable maintenance activities accurately and promptly in uncertain environments. FMEA has been used in managing risks in various scenarios, with recent research covering cold chain food transport [26], floating offshore wind turbines [27], marble production [28], and hydroelectric earth dams [29]. Its application in the railway industry includes overhead line equipment [8], electro-pneumatic braking [30], and traction power supply [31].

Failure modes can be found in six common aspects of production management—people, materials, machines, measurements, methods, and environments [32]. Each failure mode is usually assigned a risk priority number (RPN), which is conventionally the mathematical product of the failure's impact severity ($S$), the likelihood of occurrence ($O$), and ease of detection ($D$) [33], as shown in Equation (1).

$$\mathrm{RPN} = S \cdot O \cdot D. \tag{1}$$

Usually, an integer from 1 to 10 is assigned to $S$, $O$, and $D$ for the calculation. Recent research [28, 34] uses interval-valued fuzzy techniques to reflect the vagueness and hesitation in deciding the value of RPN constituents, which are no longer a single-point integer but an interval. Other factors such as safety, cost, lost time, preventability, and mitigation effectiveness [28, 34, 35] may be taken into account to more comprehensively model each failure mode.

To overcome the shortcoming that the multiplication results can be discontinuous and sensitive to a small change in the value of the constituents $S$, $O$, and $D$, Component Criticality Index (CCI) is introduced by Duque et al. [8]. The CCI is calculated as the *sum* of $S$, $O$, and $D$ (Equation (2)) so that the change to the risk priority caused by one of the parameters is independent of the other two.

$$\mathrm{CCI} = S + O + D. \tag{2}$$

Instead of having the same impact on the RPN, the $S$, $O$, $D$, and/or other parameters are sometimes weighted to reflect a focus on certain aspects of the risk [30, 34]. In complex cases, techniques of multicriteria decision making such as analytic hierarchy process [27] and data envelopment analysis [35] are used in failure mode risk ranking.

*2.3. Failure Deterioration and Control.* Emergency response is usually costly and imperfect; therefore engineers have been exploring opportunities to smooth the urgency out. A popular method is to find an optimum frequency of routine inspection so that failure can be identified early without investing a significant amount of operating expense [36]. Failure deterioration can be represented by the transition through multiple identifiable and controllable states [37, 38]. When symptoms of severe deterioration are spotted, and the repair is less disruptive, engineers can carry out the repair at a suitable time to maximise overall service availability. Figure 2 shows an example. Failure deterioration is monitored by scheduled inspections. When the deterioration is severe, early repair can be carried out before the next scheduled overhaul to prevent catastrophic service disruption. The gradually darker orange circles represent the failure deterioration, and the vertical blue lines represent maintenance activities. After severe symptoms are identified on the railway where emergency access is disruptive, engineers may apply a temporary speed restriction to slow down the failure's further deterioration in the short term [39] or arrange coasting over a few kilometres of track so that no pantograph is in contact with the overhead line to disturb the failed component.

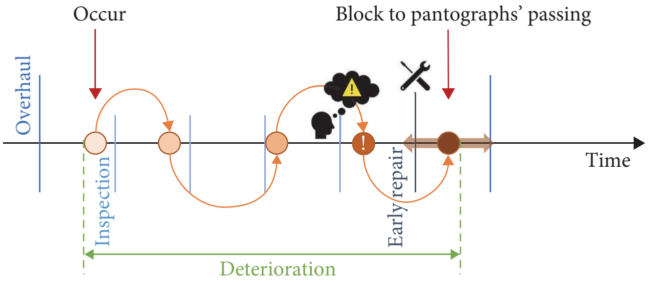


Figure 2: Failure deterioration, monitor, and control.

The success of the above relies on engineers' understanding of failure's occurrence and deterioration, which is the time between a failure's initial occurrence and the operation being severely disrupted by it (e.g., the block to pantographs' passing in Figure 2) [3]. Based on engineers' experience and data records, the failure occurrence can be modelled by exponential distribution for non-ageing equipment and Weibull distribution for ageing equipment, while the deterioration's time-related probability density function is usually exponential [40, 41].

## 3. Railway Overhead Line Rigid Stainless Steel Droppers and Multi-Strand Copper Jumpers

*3.1. Rigid Stainless Steel Droppers.* Figure 3 shows a typical span of the ECML's simple contact system, with rigid stainless steel droppers between its overhead line's contact wire and catenary wire. The convention of numbering droppers on the ECML is from small value on London-end to large value on Edinburgh-end, and each span makes a new start. The droppers are installed between two overhead line registration points, and the number of droppers in a span and their spacing are calculated from the span length (Table 1). Each span is commonly between 50 and 70 m long [25]. The

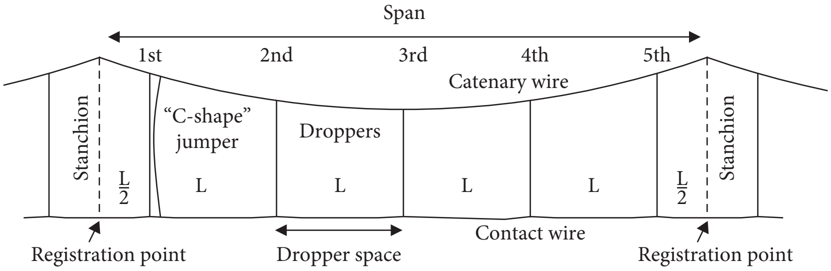


Figure 3: Simple contact wire system.

Table 1: Mk3B number of droppers in different span lengths.

| Span length (m) | Number of droppers |
|---|---|
| 75–66 | 6 |
| 65–53 | 5 |
| 52–40 | 4 |
| 39–27 | 3 |
| 26–14 | 2 |

contact wire is pre-sagged between the first and the last dropper in each span by 0.1% of the span length to limit the disturbance from passing pantographs [2]. Because stainless steel's conductivity is not sufficient for traction current flow, a "C-shape" multi-strand copper jumper is usually installed approximately every 200 m (four spans), next to the first or the last dropper in a span, to facilitate conduction between the catenary and contact wires. Figure 4 presents a variety of the in-span droppers and the "C-shape" jumper that are used on the ECML. The combination of the droppers and the jumper has a low capital cost and is still serving busy railway networks.

The droppers originally employed cam-type locking with a "key" clip (Figure 5); they are locked onto or removed from a contact wire by using a dropper key to rotate the locking cam on the clip. Bolted clips have been introduced widely to the ECML since 2014. When the stainless steel dropper wire breaks in the middle, the clips can hold the wire up, whereas the unbolted "key" clips are not designed with this function. In most similar cases with a "key" clip, the broken wire hangs below the contact wire and damages pantographs.

In regard to overbridges without much electrical clearance, the catenary wire is usually brought lower, and the overhead line's system height (the separation between the catenary wire and the contact wire) is reduced, achieving a 660 mm air gap. In such a situation, loop droppers (Figure 6) and/or smaller droppers are often used in spans approaching an overbridge. These loop droppers are not fixed to their catenary wire, and their use slightly improves the overhead line's local stiffness [1].

Where the electrical clearance is low, alumo-weld aluminium composite (AWAC) catenary wires are changed to contact wires to provide better mechanical integrity, protecting against the strands burning up from electrical discharge, usually caused by bird strikes. The section of the contact wire that replaces the catenary wire under an overbridge is called the contenary wire. The contenary wire is brought in parallel with the contact wire under the overbridge by loop droppers and small droppers (Figure 7, D3 and D2). The two wires are registered by a bridge arm and maintained in parallel by zero encumbrance clamps (Figure 7, D1). Figure 7 shows an example of a bridge approaching overhead line spans.

The top of each dropper sits on the contenary or the catenary wire with a line guard (Figure 6) or a saddle (also called "aeroplane," Figure 8) to protect the wire's mechanical integrity. The saddle's material is usually very similar to the wire's material. The top is circular and fits symmetrically around a saddle, being ∼20 mm in internal diameter.

In addition to being in-span supporting contact wires, droppers are used in cantilevers to support their structural integrity, such as nose, V-shape, and windstay droppers (Figure 9). Longitudinally, these droppers link the cantilever tubes together and reduce the risk of tubes moving individually along the track. Vertically, a nose dropper holds a long registration tube in a nearly horizontal position. Without the nose dropper, the long registration tube could rotate (up and down) around its connection to the strut tube. Very often near an overbridge where a contenary wire is used, an inverse "V" dropper assembly is installed to the cantilever to hold the wire's registration.

Failures of the droppers in design, installation, and operation, such as incorrect length, detaching, and breakage, can lead to the contact wire's substandard height. This is referred to by Song et al. [42] as a main type of contact wire irregularities that affects the pantograph and contact wire's smooth interaction. When a pantograph passes under the unsupported part of the contact wire, locally, the amplitude of both the contact force and the contact wire's vibration becomes higher [43]. Recently published research has been focusing on the failures and the dynamic performance of flexible copper droppers [44, 45] that are commonly used on modern high-speed railway electrification. In the meantime, the traditional rigid stainless steel droppers of the simple contact system are still in service across busy railway networks. Their failures are critical for the railway's high-performing operation. It remains important to systematically research the droppers' operational performance after being in service over decades.

*3.2. Multi-Strand Copper Jumpers.* In addition to the above-mentioned "C-shape" jumper, another two main types of the jumper are installed on the ECML between Cambridge Junction and Stoke Junction, full- (or double-) drape jumpers and potential equalising (PE) jumpers (Figure 10). The full-drape

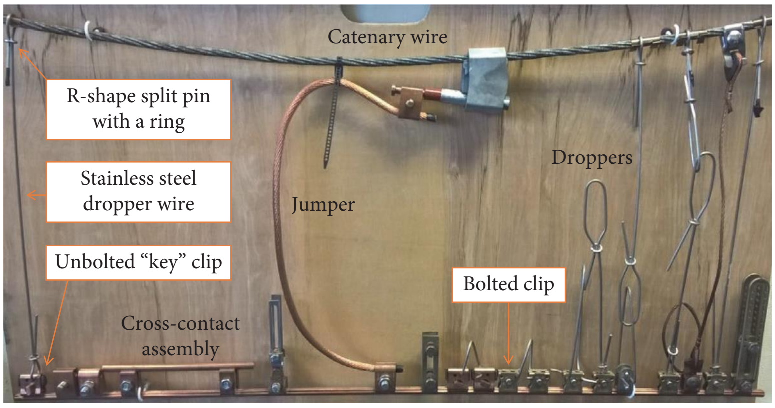


Figure 4: Various types of in-span droppers with a "C" jumper in the middle.

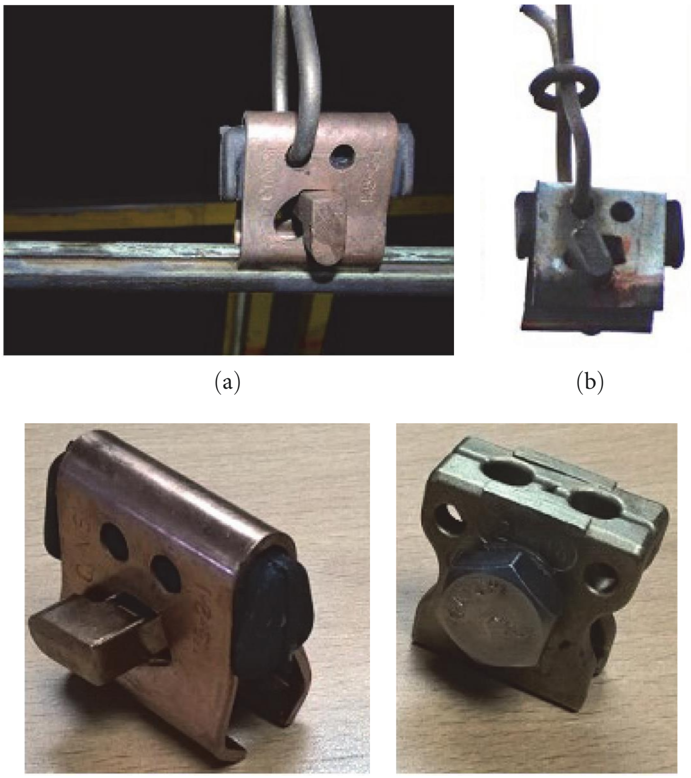


Figure 5: (a) Mk3B "key" clip is attached to contact wire, (b) damaged and detached "key" clip, (c) and (d) close view of "key" and bolted clip.

Figure 6: (a) Loop dropper in bridge approaching span with a small section of AWAC catenary wire being wrapped by a line guard and (b) loop dropper being lifted by a nearby static pantograph ~3–4 m away.

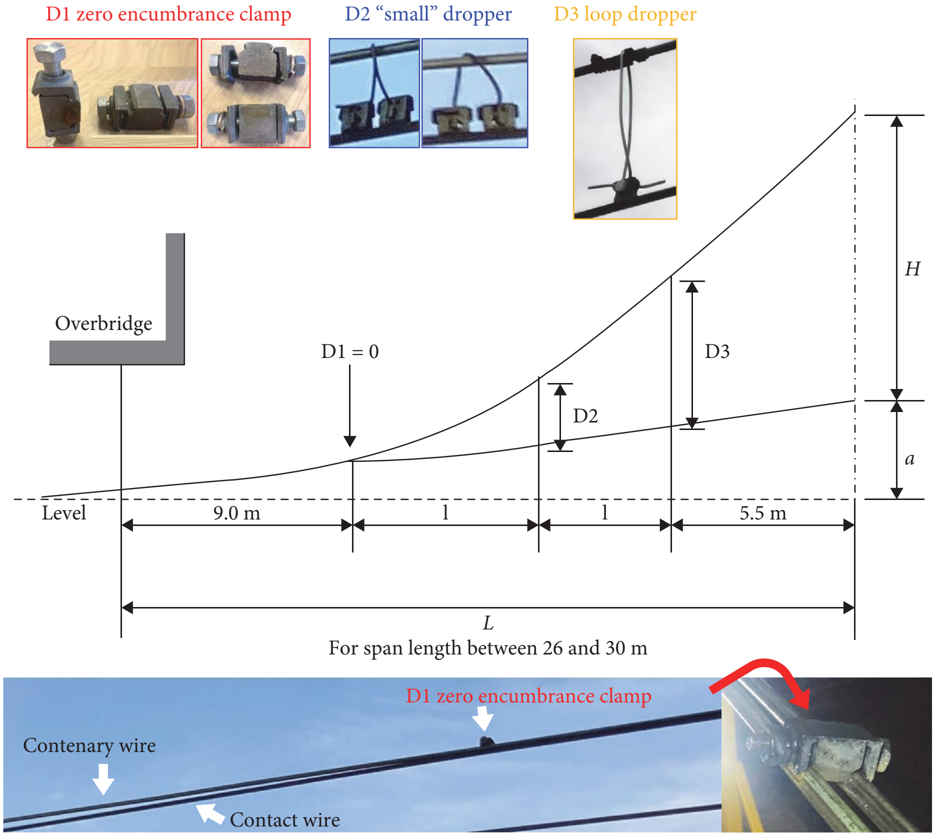


Figure 7: Bridge approaching droppers—D1, D2, and D3 in a bridge approaching span.

Figure 8: (a) and (b) View of contenary and catenary saddle and (c) dropper top fits around catenary saddle.

jumper connects two separate overhead line wire runs and is usually installed at an uninsulated overlap (Figure 11(a)) to achieve their electrical continuity. The PE jumper usually connects the "flying tail" of a wire run to its adjacent main line wire run to equalise the electric potential of the "flying tail," for no floating voltage, at an insulated overlap (Figure 11(b)). Each wire run is approximately a mile long [4, 25]. In a booster transformer-aided traction power system, the overlap of two wire runs is often alternating between insulated (with a booster transformer) and uninsulated (without a booster transformer).

## 4. Dropper Failure Modes and Effects Analysis

On the ECML with more than 100 mph pantograph passing speed and double pantographs in use, dropper failures occur frequently and cause a significant amount of delay every year, especially in the area between Cambridge Junction and Stoke Junction. Rigid droppers with little freedom of vertical movement are prone to be kinked by the pantograph's uplift contact force and the overhead line's vibration (Figure 12 left (a)–(d)). Kinks also occur on flexible droppers (Figure 12 left (e)). Online published research on overhead line droppers is mainly around the flexible droppers that are widely used for high-speed railway overhead lines. Their failure modes have been summarised and analysed comprehensively [44, 46], and herein are not discussed in detail.

After a long period of service, kinking and fatigue result in the stainless steel dropper wire breaking. Uplift and vibration may also lead to the "key" clip becoming loose and the dropper's bottom tending to shift along the axis of the contact wire towards the normal direction of travel (Figure 12 right). Although the dropper design may include the additional horizontal pulling resulting from the inclination up to 30° [47], the shift and the kink are generally considered as the dropper's failure precursors.

After a dropper wire breaks, if its bottom part hangs below the contact wire, a passing pantograph and its carbon strips will very likely come into contact with the wire and be

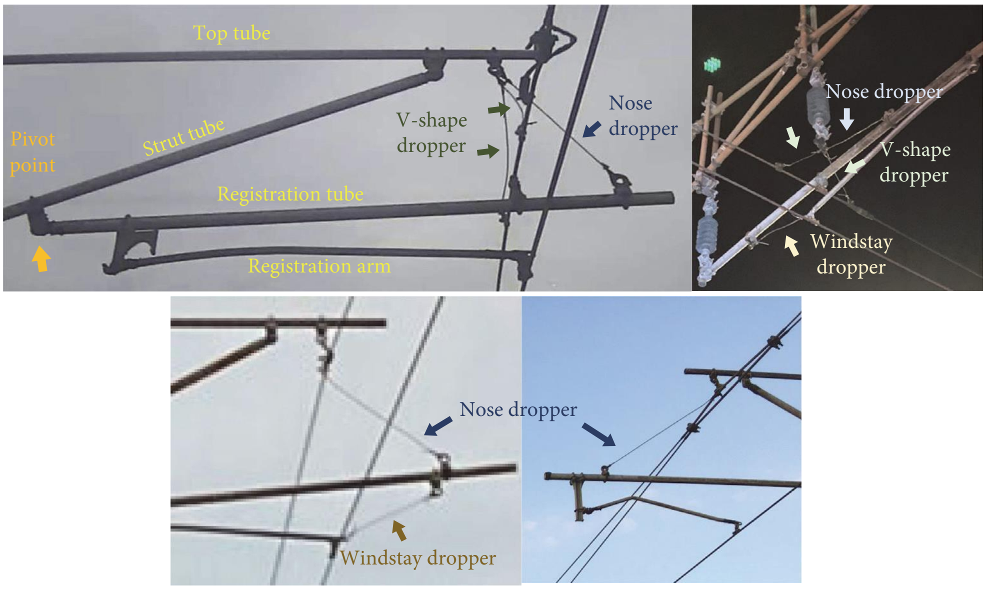


Figure 9: Cantilever droppers—nose, V-shape, and windstay.

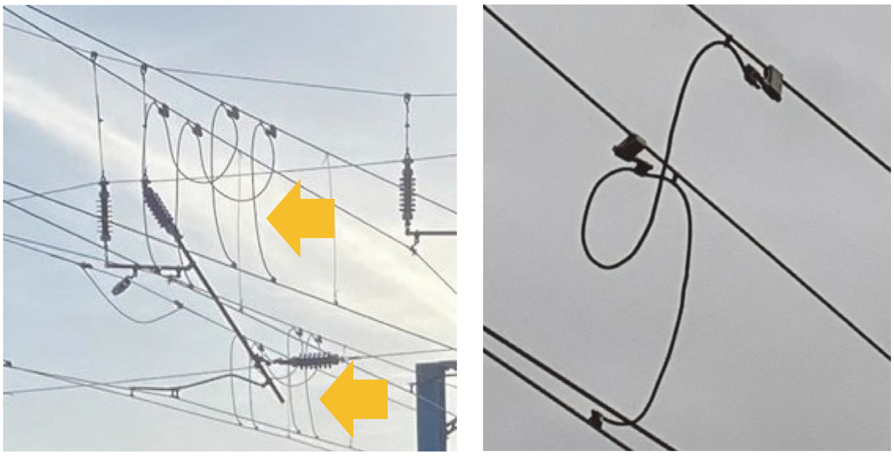
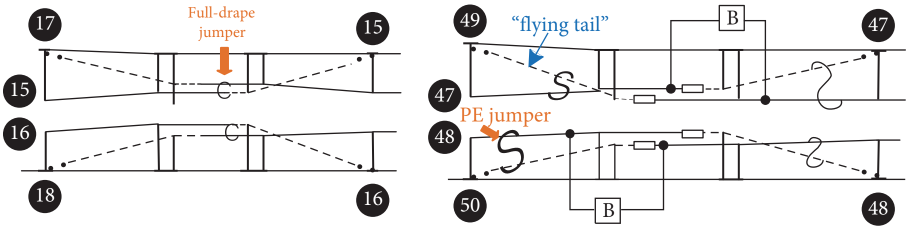
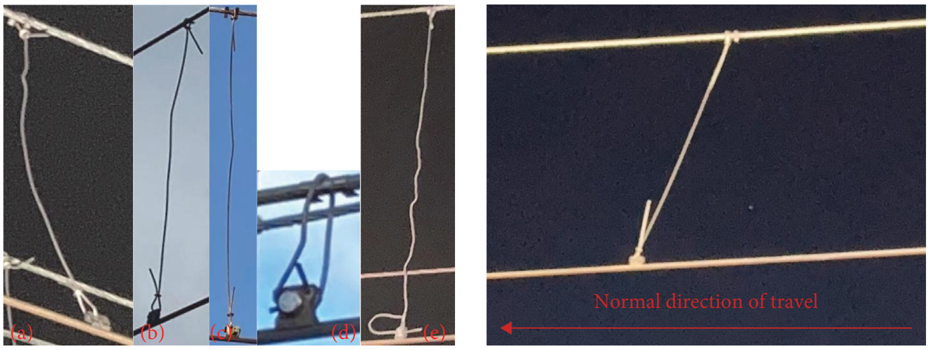

(a)
(b)

Figure 10: (a) Full-drape jumpers and (b) PE jumper.



(a)
(b)

Figure 11: (a) Overhead line uninsulated overlap with full-drape jumpers and (b) insulated overlap with PE jumpers.



Kinked dropper wires

Shifted (inclined) stainless steel dropper

Figure 12: Droppers' condition deteriorates in service before failures occur: (a–c) kinked rigid droppers, (d) kinked loop dropper, and (e) kinked flexible dropper.

Table 2: Droppers' common failure modes and effects.

| Components | | Failure modes | Causes | Effects |
|---|---|---|---|---|
| 1 Single in-span dropper—Clip | 1a | Dropper coming off | C1 and C2 | N/A |
| | 1b | Dropper detached, may hit pantographs | C1, C2, and C3 | E1 and E2 |
| | 1c | Dropper detached, clear from pantograph and contact wire | C1 and C2 | E1 |
| | 1d | Dropper detached, damaging pantographs | C1, C2, and C3 | E1 and E3 |
| 2 Single in-span dropper—Wire | 2a | Dropper wire broken, hanging below the contact wire | C1, C4, and C5 | E1, E3, and E5 |
| | 2b | Dropper wire broken, clear from pantograph and contact wire | C1, C5, and C6 | E1 |
| | 2c | Short-length dropper hogging | C4 | E7 |
| 3 Single in-span dropper—Top | 3a | Dropper top off the saddle | C1 and C4 | E6 |
| | 3b | Dropper runaway | C1, C2, and C5 | E1 |
| 4 Single in-cantilever dropper | 4 | Nose, V-shaped, windstay droppers detached/broken | C1 and C4 | E1, E2, E3, E4, and E5 |
| 5 Multiple droppers | 5a | Direct damage from a failed dropper | C9 | E1, E3, E5 |
| | 5b | Secondary damage from a failed dropper | C1 | E1 |
| 6 External objects | 6 | Objects on droppers | C8 | E3 |

Causes: C1, In-service cyclically loading; C2, Cam lock clip becoming loose; C3, Long dropper length; C4, Workmanship; C5, Broken dropper saddle; C6, Dropper wire's material deficiency; C7, Short dropper length; C8, Environment and lineside neighbours; C9, Pantograph dragging dropper forward. Effects: E1, Reduced support to contact wire's positioning; E2, Pantograph chips; E3, Pantograph damage (ADD); E4, Cantilever damage; E5, Pantograph entanglement; E6, Catenary or contenary wire damage; E7, Arcing damage to pantograph's carbon and contact wire.

damaged. On many occasions, because the unbolted dropper clip is not strongly fastened, the hanging part is ripped off by a passing pantograph and sometimes wraps around the pantograph's frame. If the dropper wraps around the pantograph in an offending pose, then it will likely sweep along the contact wire and detach the approaching droppers. In severe cases, a hanging-off dropper can lead to substantial damage on the carbon strips that activate the automatic dropping device (ADD), a pantograph's fail-safe device, and cause significant service disruption. When a pantograph collides with a failed dropper or other failed overhead line equipment, foreign objects such as wildlife or vegetation, etc., the ADD's constantly pressurised air pipe may be damaged. The pipe is wired along the pantograph's frame and under the carbon strips. The loss of air pressure will cause the failed pantograph to drop and stop it from affecting other healthy equipment.

Pantograph impact and overhead line vibration can bend a rigid dropper and cause the "key" clip to detach from the contact wire. In addition, though infrequently, the top ring can be gradually pushed loose, and finally drop, from the R-shape split pin that is hung on the catenary wire. After a dropper is broken or detached, the weight of the contact wire is shared by its adjacent droppers. If a broken dropper is not repaired promptly, its adjacent droppers are more likely to detach from the contact wire. Due to their severe potential effects, failed droppers are usually treated with a high priority on high-speed lines. A single dropper off or broken may need to be repaired within a week; two consecutive droppers off or broken usually require an emergency repair before the service starts in the second morning; and three may render the pantograph's passage unsafe or completely blocked.

The above-mentioned dropper failure modes, causes, and effects are summarised in Table 2. Four years' maintenance

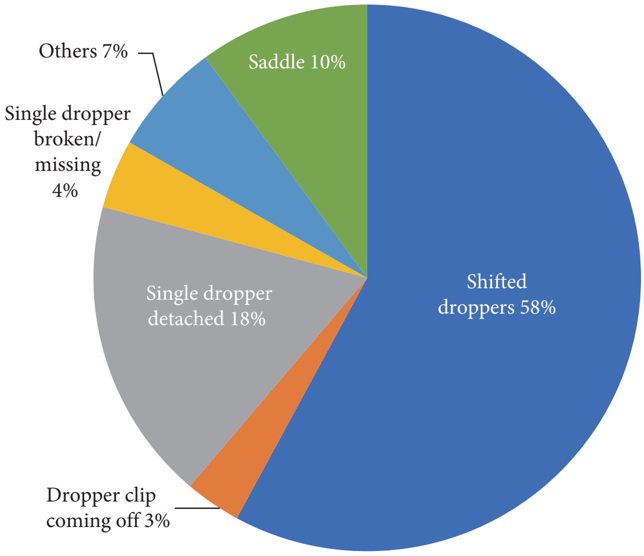


FIGURE 13: Dropper failure modes' proportion in 4 years' maintenance record, 4,050 entries in total.

TABLE 3: Distribution of four main dropper failure modes per line direction and speed.

| Failure modes | North : South direction failures ratio | Fast : Slow speed failures ratio | Failures on slow speed lines in the 4 years | Fast speed lines weekly failure rate |
|---|---|---|---|---|
| Shifted droppers | 47 : 53 | 96 : 4 | 84 | 11 |
| Dropper clip coming off | 58 : 42 | 99 : 1 | 1 | 0.6 |
| Single dropper detached | 44 : 56 | 99 : 1 | 4 | 4 |
| Single dropper broken/missing | 44 : 56 | 98 : 2 | 4 | |

records of 4,050 dropper-related work orders on the ~100 km railway between Cambridge Junction and Stoke Junction have been analysed in this paper. The area includes two fast lines in the centre with ~125 pantographs passing per direction per day at more than 100 mph and two slow lines on the outer having ~85 pantographs passing per direction per day at 75–80 mph. The proportions represented by the various dropper failure modes are presented in Figure 13. The occurrence of the four most common modes shows no distinction between pantograph travelling directions and has been very unlikely on the slower lines (Table 3).

The data includes 146 transitions between single-dropper failure modes, and 84 of the transitions are shifted droppers deteriorating. The transition time is presented in a histogram (Figure 14). The failure modes' identification and transition show no surge in a specific year or quarter in the 4-year period. Many failure modes are also applicable to flexible droppers, though their rate of occurrence is much less than that of the rigid stainless steel type. The following subsections analyse each of the failure modes in Table 2 in detail.

### 4.1. Single In-Span Dropper—Clip (Failure Mode 1)

*4.1.1. Dropper Coming Off (Sub-Category 1a).* Dropper coming off is an important failure mode of cam lock "key" clips (Figure 15). It is identifiable during ground-level inspection with due diligence. Clips that show signs of partially detaching are more vulnerable to come completely off the contact wire. In the 4-year period, 1% of 2,317 shifted droppers became coming off, and 27% of 135 coming-off droppers came off (detached). The data show 11% of the 135 coming-off droppers detached within 3 months of them being identified as coming-off, and the percentage increases to 19% in 6 months and 24% in 12 months.

*4.1.2. Dropper Detached, May Hit Pantographs (Sub-Category 1b).* Although a detached dropper hanging above the contact wire may seem harmless, passing pantographs push the contact wire up and may hit the dropper. When a pantograph moves along the contact wire, it applies an uplift force, typically 70–90 N. In the studied railway patch with Mk3B overhead line equipment and Class 91 electric locomotives, at zero wind speed, the wire uplift can be 35–65 mm for train speeds of 70–120 mph. Increasing the wind speed may increase the wire's uplift. Although detached droppers are likely to hit passing pantographs, with the maximum line speed being 125 mph, mostly the damage is a minor chip on the pantographs' carbon that does not affect its functioning in the short term.

Figure 16 shows rigid stainless steel droppers detached from the contact wire. Except for the first Figure 16(a), the photos were taken with a pantograph next to the dropper, and the contact wire was lifted slightly by the pantograph's uplift. The detached dropper in Figure 16(f) is rarely seen—its clip was parted and gone. Without the mass of the dropper clip, its potential damage to passing pantographs is less severe.

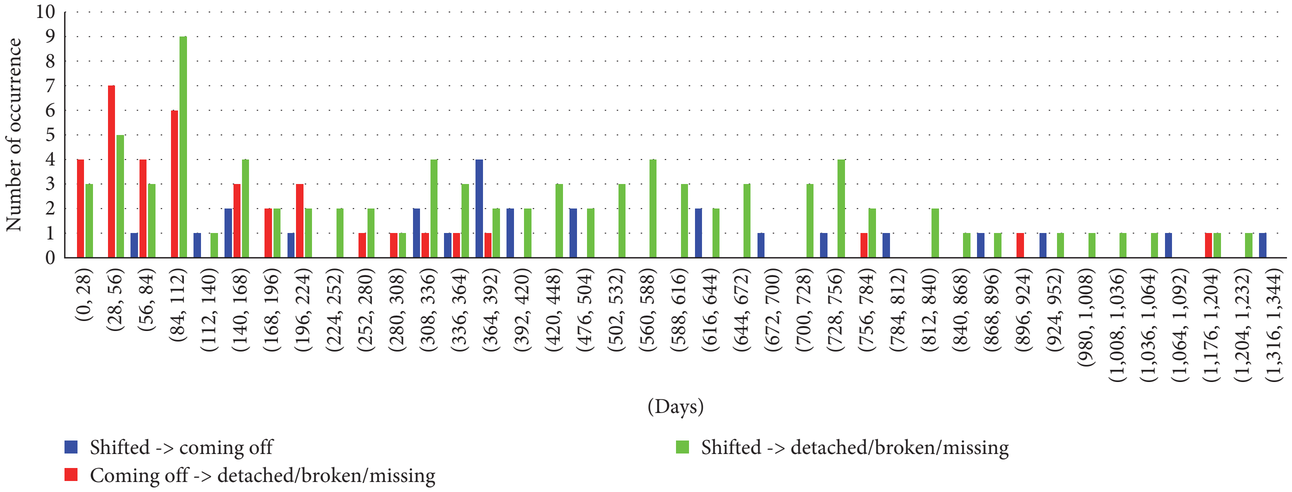


Figure 14: Histogram of dropper failures' state transition.

Figure 15: Droppers coming off contact wire.

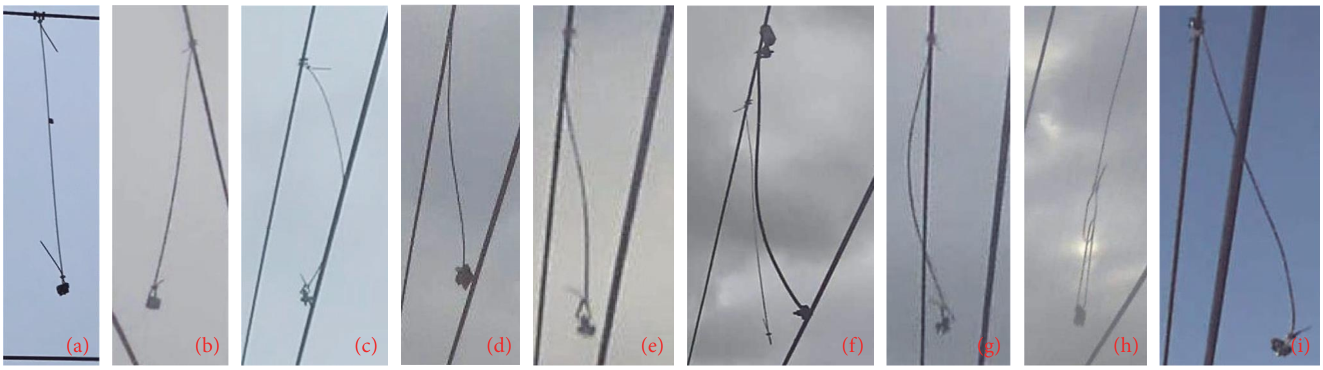


Figure 16: Detached droppers: (a) from ground-level inspection and (b–i) from train-borne pantograph camera.

*4.1.3. Dropper Detached, Clear from Pantograph, and Contact Wire (Sub-Category 1c).* A detached dropper may move away from the pantograph–contact wire interface, sometimes because of it being hit by passing pantographs multiple times. Examples are shown in Figure 17. The detached dropper in Figure 17(c) is rarely seen—the clip was broken, and the wire came out of the clip. The failure mode also applies to flexible droppers such as Figure 17(f), not discussed in detail herein.

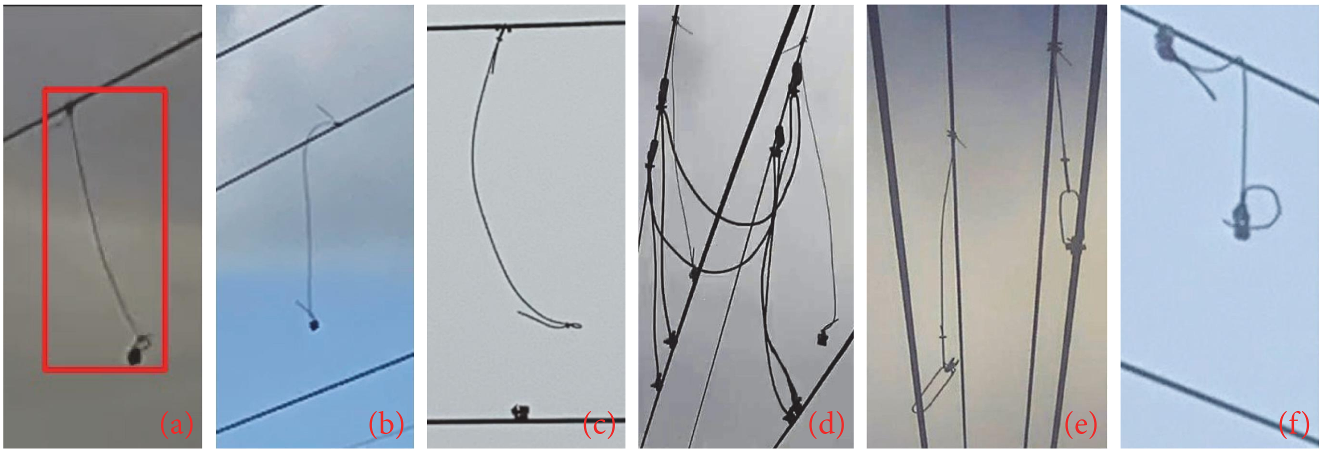


Figure 17: Detached droppers clear from pantograph–contact wire interface: (a), (d), and (e) from train-borne pantograph camera and (b), (c), and (f) from ground-level inspection.

Figure 18: Detached dropper damages passing pantograph, 1 -> 2 -> 3.

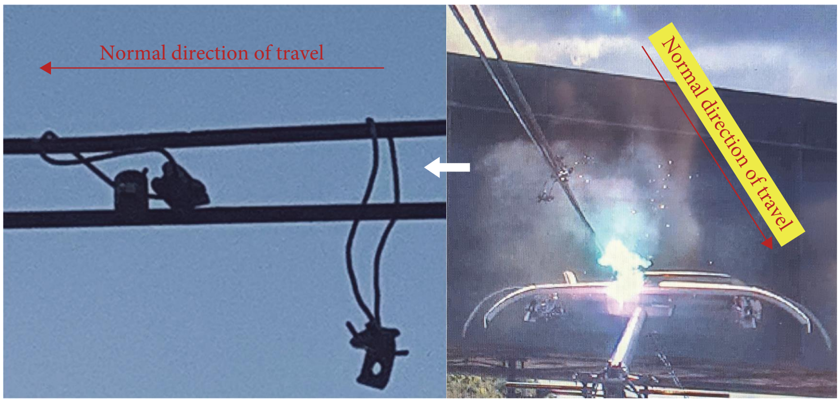
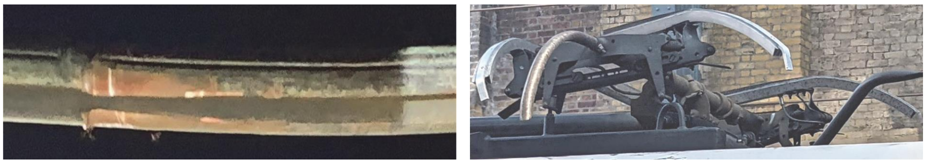


Figure 19: Failed dropper damages passing pantograph and the next dropper.

The pictures of detached droppers in Figures 17(a–c) and 17 (f) were taken without a pantograph's uplift.

*4.1.4. Dropper Detached, Damaging Pantographs (Sub-Category 1d).* Figure 18 records a detached dropper hanging below the contact wire and damaging the passing pantograph severely such that ADD was activated. After an ADD is activated, according to Rule Book Modules: Electrified lines (AC) [48], the affected line's speed shall be restricted to 20 mph until the overhead line equipment is examined by competent staff on the ground. The emergency speed restriction and its duration can be very disruptive to the railway's operation.

Figure 19 shows a similar situation, but the droppers are of different types in a bridge approaching span. A failed loop



The dragging mark on the contenary wire

The damaged pantograph

Figure 20: Damages of the loop dropper incident.

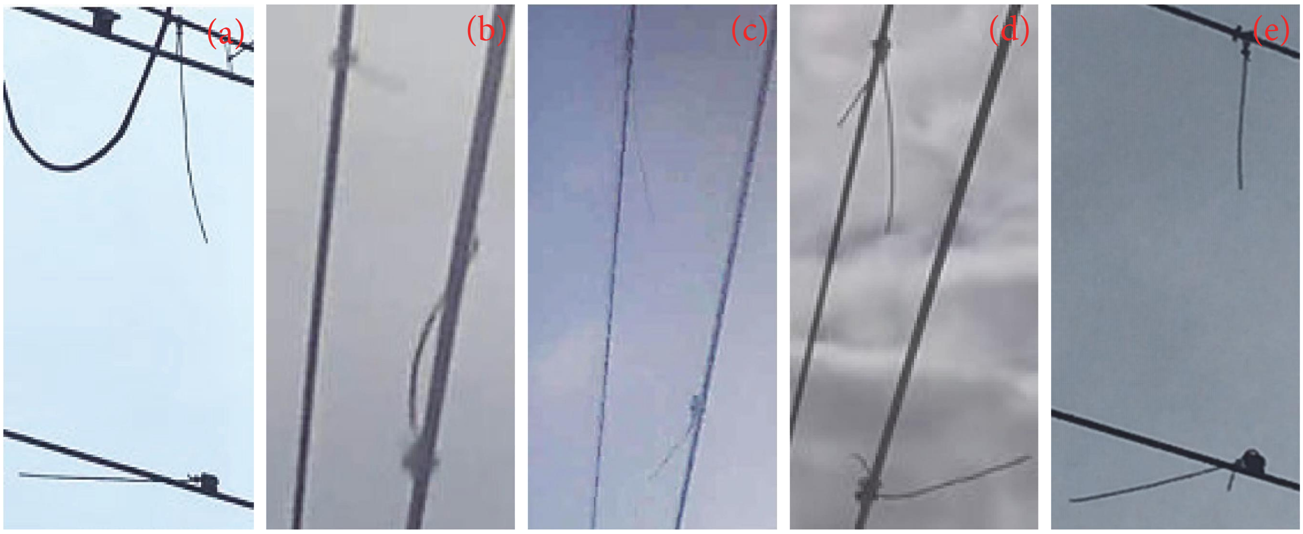


Figure 21: Broken droppers hanging below (a) and (c–e) or resting on (b) contact wire.

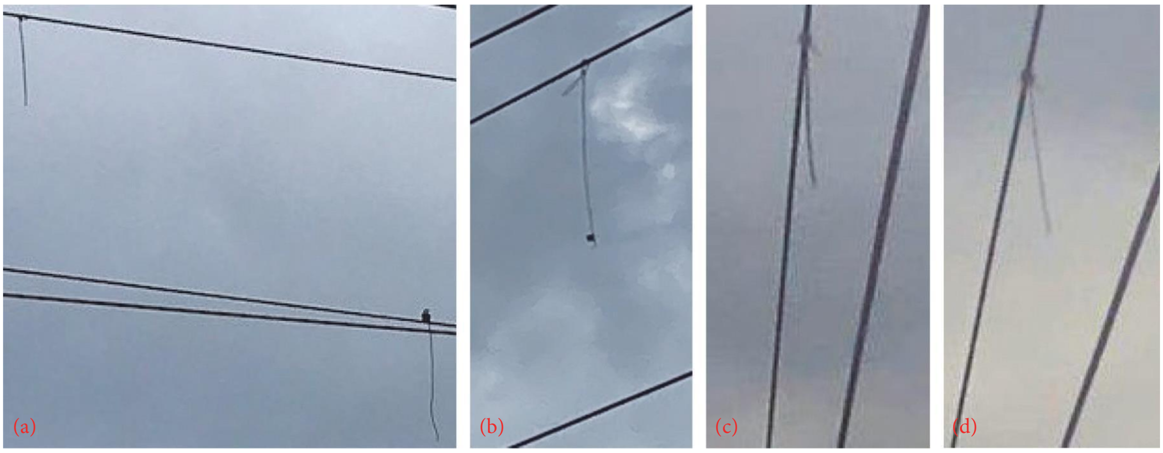


Figure 22: Droppers with their bottom part having moved forward (a) or missing (b–d).

dropper was brought forward by a pantograph and damaged the approaching small dropper. The contenary wire was damaged by the dragging, and the leading frame of the pantograph was destroyed (Figure 20). The incident initially caused 847 min delay in train services.

### *4.2. Single In-Span Dropper—Wire (Failure Mode 2)*

*4.2.1. Dropper Wire Broken, Hanging Below the Contact Wire (Sub-Category 2a).* Rigid stainless steel dropper wires can break due to long-term fatigue accumulation. Figure 21 shows a normal scenario whereby the broken dropper wires with an unbolted "key" clip have failed. The bottom half is hanging below the contact wire and threatening pantographs' passage, Figures 21(a) and 21(c)–21(e), or less likely, laying on the contact wire Figure 21(b). The bottom part is highly likely to be hit by a passing pantograph before the failure is reported. After the hit, the bottom half is either moved forward, as shown in Figure 22(a), or taken away by the pantograph in Figure 22(b)–22(d).

Usually, this failure mode does not damage pantographs severely. However, a broken dropper wire may wrap on a pantograph and occasionally damages the ADD's air pipe. As

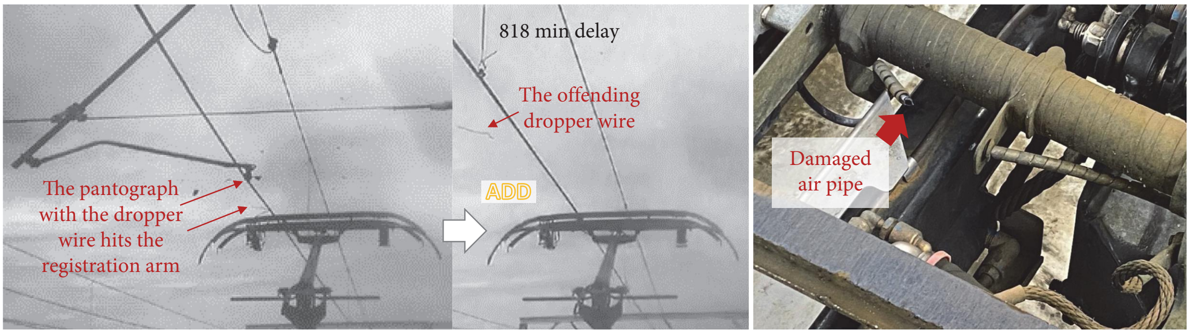


Figure 23: Broken dropper wire wraps on pantograph and hits the upcoming registration arm.

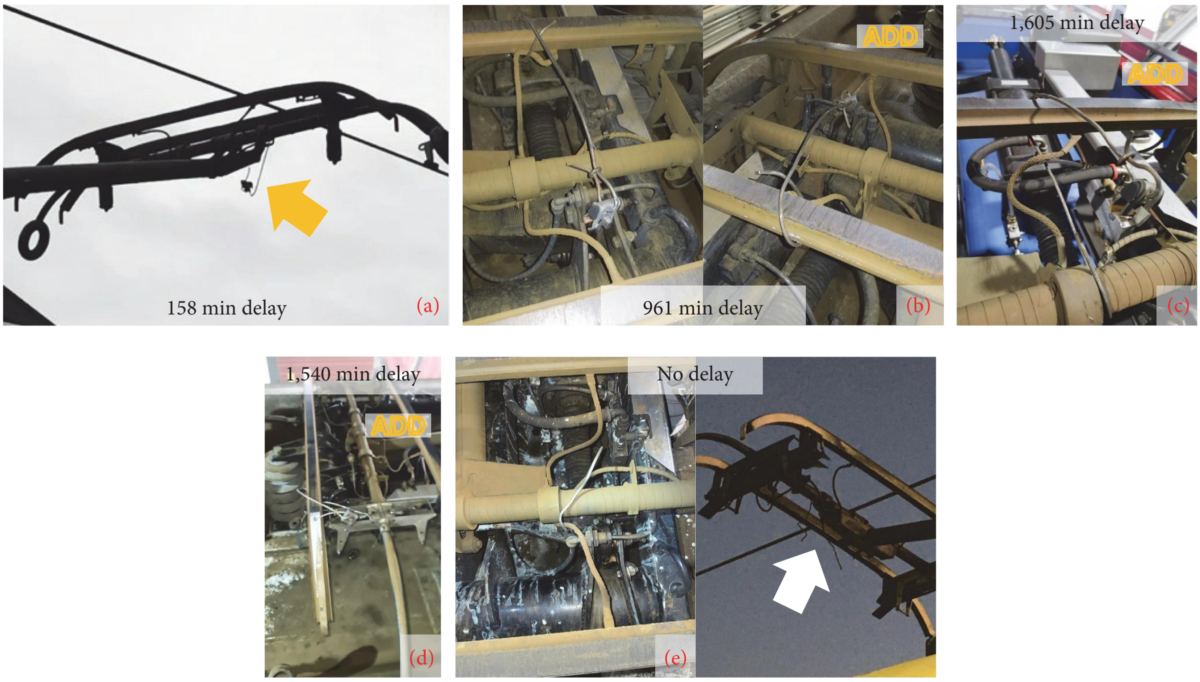


Figure 24: Incidents of broken dropper wire wrapping on pantograph: (a) and (e) no ADD activation and (b–d) ADD being activated.

a consequence, the air leaks, and the pantograph drops. In Figure 23, the wire of the dropper prior to the registration arm broke, and the broken wire's bottom part wrapped on the passing pantograph. They hit the registration arm at 114 mph. The pantograph was damaged and its ADD operated. If either the dropper had been in a less offensive pose or the ADD had operated on time, other equipment would have not been damaged such badly. Figure 24 shows another five incidents. The risks in both Figures 24(a) and 24(e) were identified and addressed early; severe consequences were averted: Figure 24(a) was reported by staff at a station, and Figure 24(e) was reported by onboard staff after seeing "*sparking coming down onto the track.*" Figure 24(b)–24(d) had ADD activation and a significant impact on the railway's operation. In very rare situations like Figure 25, a broken dropper wire penetrates the pantograph's frame and significantly disrupts train services.

*4.2.2. Dropper Wire Broken, Clear from Pantograph, and Contact Wire (Sub-Category 2b).* When a dropper wire breaks, the possibility of it remaining above or falling below the contact wire depends on the type of the dropper clip being used at its base. The unbolted "key" clip is more likely to allow a broken dropper wire to drop below the contact wire, and it relies on its inside rubber's friction to maintain the elevation of the broken wire. The bolted clip can keep a broken dropper wire clear of the pantograph–contact wire interface because the bolted connection allows the base wire loop to be locked into its position, preventing any rotation towards the contact wire. In Figure 26, the dropper Figure 26 (a) had an unbolted "key" clip, and it was a very rare occurrence that the bottom half was still up, whereas the droppers in Figure 26(b)–26(d) were attached to the contact wire by a bolted clip. The loop dropper Figure 26(e) broke with the top half missing, and the loop dropper Figure 26(f) broke at its

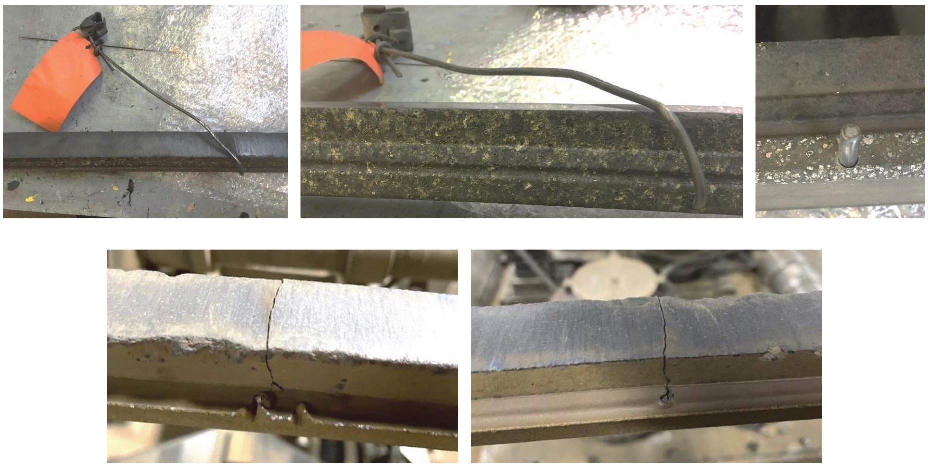


Figure 25: Broken dropper wire penetrates pantograph frame.

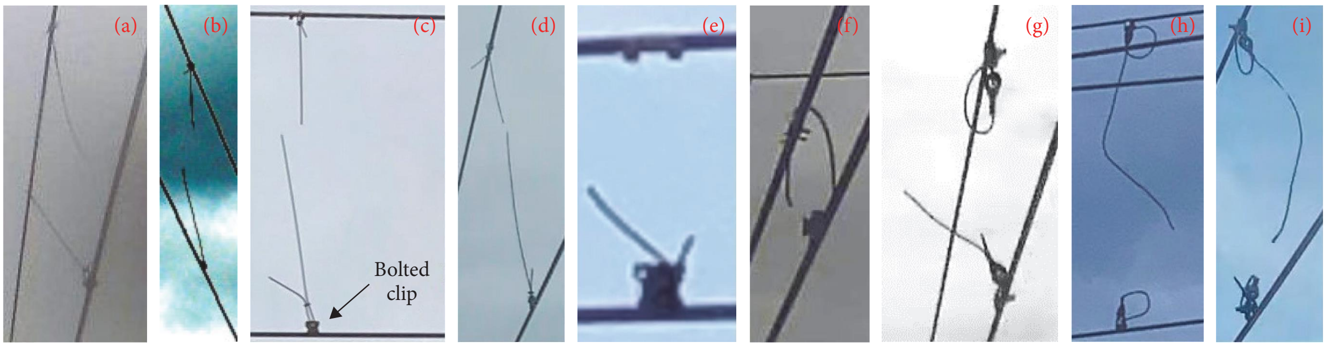


Figure 26: Broken dropper wires remain up and clear from pantograph–contact wire interface: (a), (b), (d), (f), and (g) from train-borne pantograph camera and (c), (e), (h), and (i) from ground-level inspection.

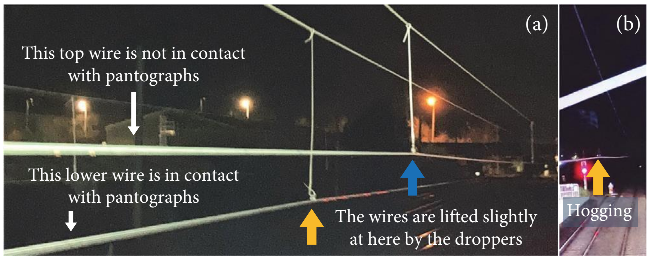


Figure 27: Dropper hogging at the arrow points: (a) in overlap and (b) on plain line.

clip and off its saddle. The failure mode also applies to flexible droppers in Figure 26(g)–26(i). The broken flexible dropper Figure 26(g) defies the expectation that it would wilt as the broken bottom half remained in its up position until it was replaced.

*4.2.3. Short-Length Dropper Hogging (Sub-Category 2c).* Dropper hogging (Figure 27) is a localised increase in contact wire's height due to a shorter dropper length. This is also referred to as contact wire height irregularity by Song et al. [42]. It does not affect rail services immediately. A slightly shorter length dropper is either designed to lift the wire in an overlap (the blue arrow) or unintended (the yellow arrows). Often an arc is generated in the loss of contact between the contact wire and a high-speed passing pantograph. The arc damages both the pantograph's carbon and the contact wire, e.g., voiding in the copper [49].

### *4.3. Single In-Span Dropper—Top (Failure Mode 3)*

*4.3.1. Dropper Top Loop Off the Saddle (Sub-Category 3a).* For AWAC catenary wires, the correct orientation of the dropper saddles is critical to prevent rapid catenary failures. Incorrect orientation of dropper saddles, e.g., upside down, can lead to a stainless steel dropper's top loop bearing directly on its catenary wire and cutting the aluminium strands (Figure 28). Incorrect orientation can be caused by the catenary wire twisting over time or works involving disturbance to the catenary, e.g., splice repairs, along track cantilever and bridle adjustments, and the installation and removal of wedge connectors. Dropper saddles have sharp edges, which can also cut the catenary wire during twisting. Incorrect formation of the dropper's top and insufficient dropper length can accelerate the cutting.

For contenary wires, the saddle's protection is also not risk-free. Investigation of the previously mentioned incident (Figures 19 and 20) found that the stainless steel dropper wire wore into its saddle and contenary assembly (Figure 29). This is very hard to spot from the ground. This makes regular high-level inspection important and necessary to identify and prevent wires being severely worn.

Figure 28: Dropper's top loop cuts into aluminium–steel catenary wire.

Figure 29: Contenary wire (a) and saddle (b) having been worn by stainless steel dropper loop.

Figure 30: Droppers off the saddle at the top: (a), (d) and (e) from ground-level inspection and (b) and (c) from train-borne pantograph camera.

Figures 30(a) and 30(b) show another frequent problem of loop droppers that can cause similar damage to that in Figure 29(a). As is briefly mentioned in Section 3, because of the freer movement of the loop droppers' top during a pantograph's passage, the droppers can move off the saddle and rest on the contenary wire. Figure 30(c) shows an uplift dropper's top off the saddle. Because of the room for vertical movement being provided by the two linked loops, the top is pushed less by pantographs, and the top off-the saddle occurs less often than other types of stainless steel droppers. Figure 30(d) shows a bottom-shifted dropper's top off the saddle due to the wire's vibration and along-track pulling. Because of the top's smaller size, off the saddle occurs less often with those droppers than with the loop droppers in Figures 30(a) and 30(b). Figure 30(e) presents the very rare occurrence that the top opened from the catenary wire.

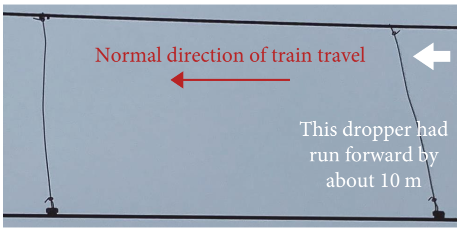


Figure 31: Runaway dropper remains attaching to the contact wire.

Figure 32: Detached dropper runs away.

Without a bolted or other similar type clip, the detached wire would have hung below the contact wire like those broken droppers in Figure 21.

In the 4-year maintenance record, 10% of the 4,050 work orders are saddle related, being distributed on the up and down direction in a ratio of 45 : 55 and the distribution on Fast and Slow line being 87 : 13. The failure mode's occurrence has no surge in any specific year or quarter.

*4.3.2. Dropper Runaway (Sub-Category 3b).* Dropper runaway is usually caused by the top coming off its saddle and the bottom fastening being loose or completely failed. It results in the contact wire's substandard positioning. The dropper's clip can become loose, especially when the clip is of a cam lock type. In Figure 31, the runaway dropper's saddle was broken (outside the picture, still at its original location), and the top was no longer held by the saddle.

When a dropper has detached or its wire has broken, the likelihood of the top coming free from its saddle is increased as there is no longer the "dropper clip–contact wire" connection that retains the dropper's position. Figure 32 shows a detached dropper having run away but been stopped by its neighbour.

*4.4. Single In-Cantilever Dropper (Failure Mode 4).* In most cases with a failed nose dropper, the long registration tube falls into the trains' kinematic envelope and blocks the line (Figure 33(a); the falling cantilever tube is earthed by a long blue cable as it is close to the staff on the ground). Where the registration is also held by an inverse "V" dropper assembly, though the tube is unlikely to fall significantly after the nose dropper detaches, engineers need to consider the minimum contact wire height being compromised. In Figure 34, the contact wire height fell 160 mm as a consequence of the nose dropper detaching. Because the inverse "V" shape dropper held the registration tube, the normal pantograph passage was not affected. The falling can be seen in the picture before and after the nose dropper is re-attached. Figure 33(b) shows a broken windstay dropper. Its bottom part is likely to come into contact with passing pantographs and has to be removed. As these droppers either do not hold the overhead line's weight or are not directly involved with the pantograph's uplift (and the overhead line's vibration), their failure occurs very rarely. Mostly, their failures are no fault of their own but are caused by, for example, a falling tree or the cantilever collapsing and being struck by a pantograph.

*4.5. Multiple Droppers (Failure Mode 5).* While multiple dropper failures are classified as their own failure mode, they are also a consequence of or have overlap with, the above-mentioned failure modes. Most multiple-dropper failures occur in one of two ways. Firstly, a failed dropper wire may entangle itself in a pantograph's frame in an offensive pose but does not trigger the ADD to operate (or not early enough). As the compromised pantograph moves along its path, the dropper wire may push off or damage the approaching equipment (Section 4.5.1). This knock-on effect can become exponential and may lead to the overhead line being unfit for further pantograph passage and requiring emergency repair. Secondly, after a single dropper fails, the adjacent droppers are supporting a greater mass and tension than before. This encourages adjacent droppers to fail. The overhead line is still fit for pantograph passage, though an emergency speed restriction may be required (Section 4.5.2). Out of the 4 years' 4,050 dropper-related work orders, 26 are multiple dropper failures, with 20 of these being adjacent and 6 being discontinuous but in the same span.

*4.5.1. Direct Damage from a Failed Dropper (Sub-Category 5a).* In Figure 35, the last dropper (−1) from the previous span failed and was brought forward by a pantograph. Wrapping on the pantograph in an offending pose, it detached all five droppers in the approaching span and was picked by the registration arm at the end of the span. The dropper did not damage the pantograph badly enough to activate the ADD. This incident only occurred once in the 4-year period. It was on a 125 mph fast line, and the failed droppers were spotted by the driver of a normal running train. The line was blocked to electric traction immediately until an emergency repair was completed, with 973 min delay in train services.

Similar incidents, slightly more common and less disruptive, are shown in Figure 36. The failure in Figure 36(a) was found during a routine patrol. The 4th dropper in the span was broken with its bottom half missing, while the top part reached to the detached 5th dropper. The bottom half of the broken dropper was hanging off the contact wire. It was brought forward by a pantograph and hit and detached the

(a) (b)

FIGURE 33: (a) Far end of registration tube falls after nose dropper fails and (b) broken windstay dropper.

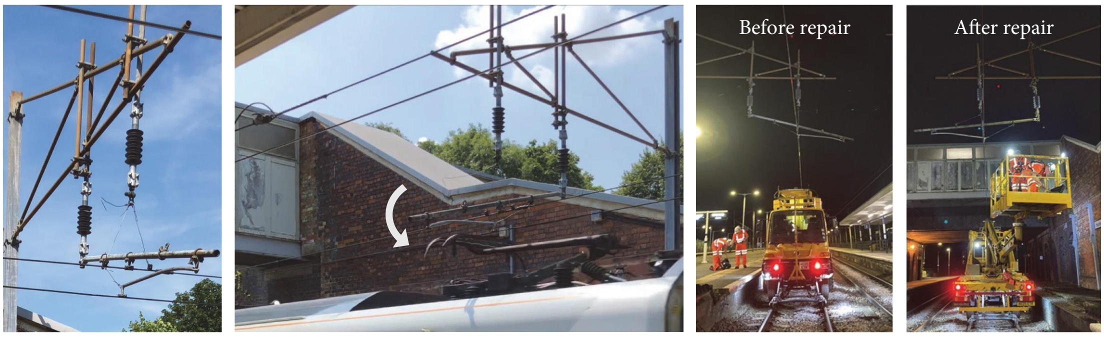


FIGURE 34: Detached nose dropper leads to registration tube falling at far end.

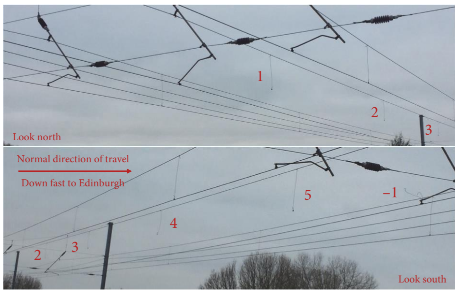


FIGURE 35: Multiple droppers detached.

dropper ahead. Onsite risk assessment decided to implement an 80 mph emergency speed restriction on the 125 mph fast line to reduce the likelihood of their adjacent droppers failing under increased vibration. It caused 234 min delay in train services. In Figure 36(b), the failure of the 2nd and the 3rd dropper was also found during a routine patrol. It took ~5 hr from the failure being identified to a minimum repair being completed, with 219 min delay in train services. The same failure mode occurred in Figure 36(c) and this was reported by a driver.

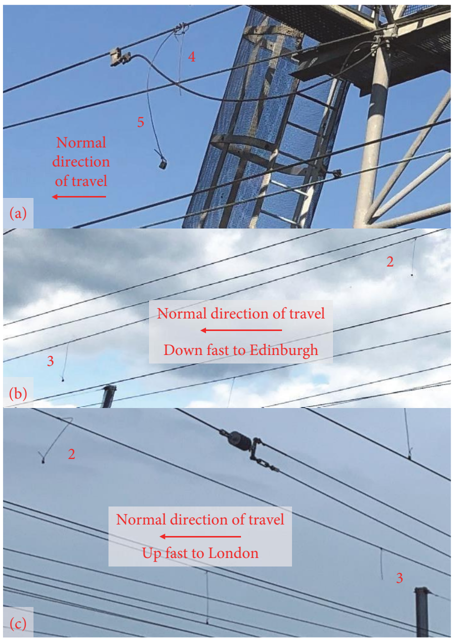


FIGURE 36: Failures of two consecutive droppers, one broken and the other one detached (a–c) from ground-level inspection.

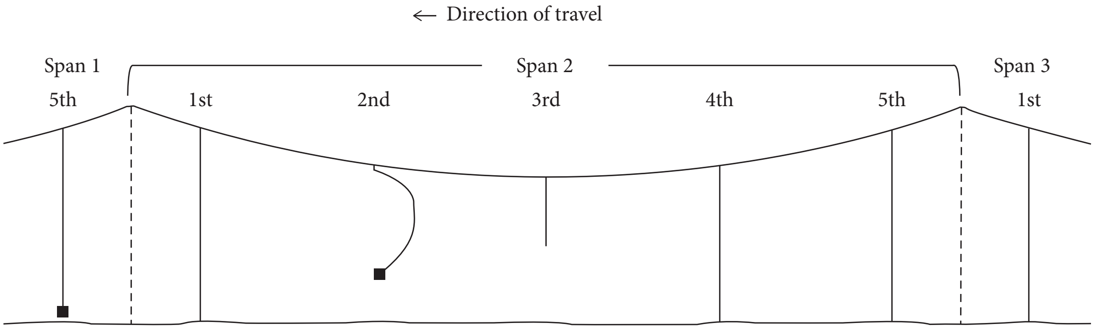


Figure 37: Failure of three droppers (dropper numbering value is reset in each span).

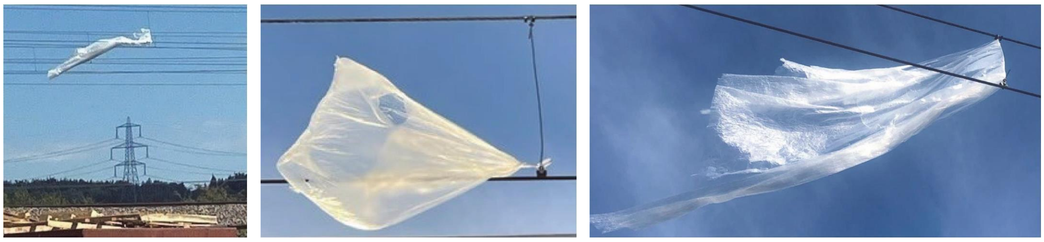


Figure 38: Plastic being held by droppers.

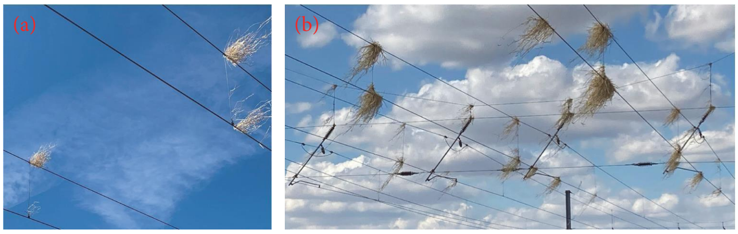


Figure 39: Hay on droppers at two different locations: (a) next to level crossing and (b) next to farmland.

*4.5.2. Secondary Damage from a Failed Dropper (Sub-Category 5b).* In the failure in Figure 36(c), another dropper in its next span was found detached. The full picture of the three droppers' failure is drawn in Figure 37. The 5th dropper in Span 1 failed due to the increased vibration after the initial failure of the 2nd and 3rd droppers in Span 2. An 80 mph emergency speed restriction was implemented to reduce the wire vibration that could have further compounded the failure. The failure was found in a weekend of reduced train services and only caused 39 min delay.

*4.6. External Objects (Failure Mode 6).* Droppers, like other overhead line equipment, can catch flying objects, such as plastic (Figure 38) and hay (Figure 39). The objects can damage high-speed passing pantographs or short-circuit over an insulator and need to be removed. The removal and the temporary block to pantograph passage often disrupt train services.

## 5. Jumper Failure Modes and Effects Analysis

The risk of jumper failure is arguably less than that of a dropper. The impact of the failure can be at one of two extremes—causing either severe service disruption or no service delay at all. Therefore, in this section, jumper failure modes are classified into two categories—service-affecting and non-service-affecting. Pictorial evidence is provided to aid the explanation.

*5.1. Service-Affecting Failures.* Service-affecting failures occurred once in every 2 years on the ECML between Cambridge Junction and Stoke Junction. Two main types both involve dangling jumpers damaging passing pantographs.

First, the jumper may detach or break at its clamp. This results in the full length of the jumper leg being free to move and likely to be struck by a passing pantograph, such as the jumper in Figures 40 and 41, where the detached full-drape jumper was identified by a diesel train's driver and was removed by staff on the ground using live line cutters.

Second, the relative movements of the two wire runs can pull the jumpers tight (Figure 42) or push them sagging (Figures 43 and 44). The former does not affect train services in the short term. The latter shows the importance of checking jumper condition and maintaining a mechanical clearance (on the ECML, the clearance needs to be minimum 300 mm) between the jumper's belly and the lower contact

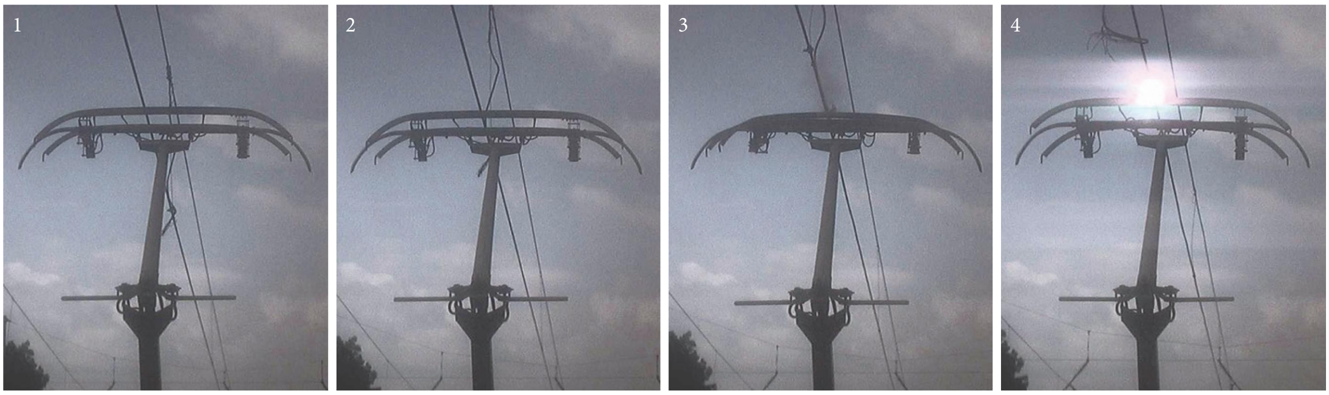


Figure 40: Failed “C-shape” jumper hits passing pantograph, 1 → 2 → 3 → 4.

Figure 41: One leg of a full-drape jumper comes out of its clamp.

Figure 42: Tight potential-equalising (a–e) and full-drape (f) jumpers.

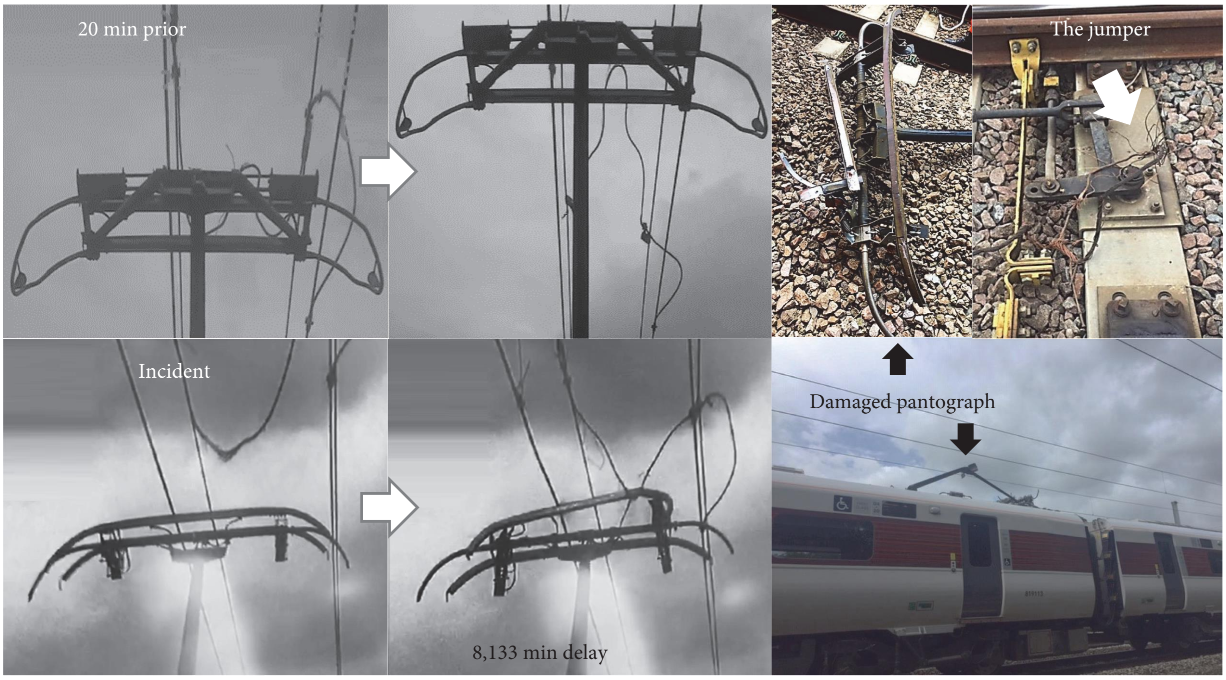


Figure 43: Loose jumper is caught by open-end pantograph and causes substantial overhead line damage.

Figure 44: Loose jumper hits passing pantograph, 1 → 2 → 3 → 4.

wire during a high-level inspection. The movements are usually considered in deciding the failure rectification timescale and reviewed in preparation for weather readiness.

The overhead line's along-track movement $\Delta L$ due to temperature changes can be calculated similarly to calculating a metal's thermal expansion (Equation (3)).

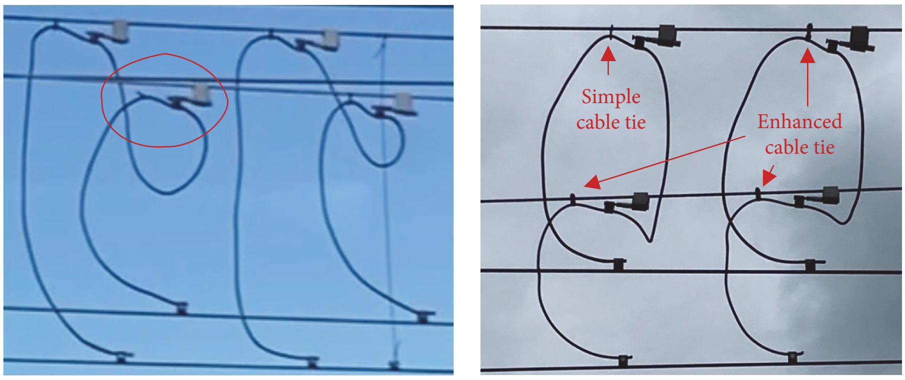
$$\Delta L = L \cdot \alpha \cdot \Delta T. \tag{3}$$

The thermal expansion parameter $\alpha$ is conventionally chosen as $\alpha = 1.75 \times e^{-5}$ (unit: 1/K) for the Mk3 overhead line equipment on the ECML. $L$ is the distance to the wire run's mid-point fixed anchor (unit: metre), and $\Delta T$ is the change of the overhead line's temperature (unit: K), which is usually different to the ambient temperature. In the middle of an uninsulated overlap, if the $L$ values of wire runs (a wire run is usually anchored at its middle point. The $L$ value being used in this calculation is approximately half of the wire run's whole length) 15 and 17 are $L_{15} = 870$ m and $L_{17} = 930$ m and the temperature is 10 K different to their installation temperature, then the relative movement between the two wires will be calculated in Equation (4).

$$\Delta L = (L_{15} + L_{17}) \cdot \alpha \cdot \Delta T = 0.315\,\text{m}. \tag{4}$$

### 5.2. *Non-Service-Affecting Failures.*

The most common failure mode of a jumper assembly is its broken or missing black cable tie (Figure 45), which fastens the jumper cable to its catenary wire, mostly due to long-term overhead line vibrations and the plastic material deteriorating under ultraviolet light. The simple cable tie has been gradually replaced with an enhanced type that has better resistance to wear and tear. Second, jumpers are prone to failure of other multi-strand cables, such as caging (Figure 46). These failures are not service-affecting and can be rectified in a longer timescale when less disruptive access is available. The dropper's coming-off state is also applicable to jumpers; their clamp on the contact wire is sometimes found coming off (Figure 47) like the dropper clips. A common feature of the coming-off jumper clamp is significant yellow corrosion. This symptom



(a) (b)

Figure 45: (a) Broken simple cable tie of full-drape jumper and (b) full-drape jumper with enhanced cable ties.

Figure 46: Caged jumper near overhead line neutral section.

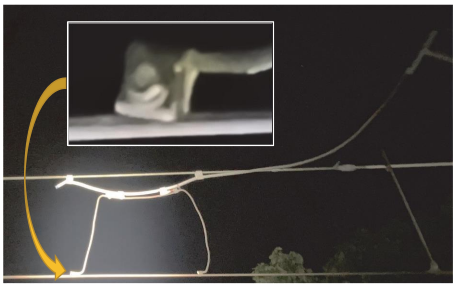


Figure 47: Jumper's clamp coming off with neutral section at right-hand side.

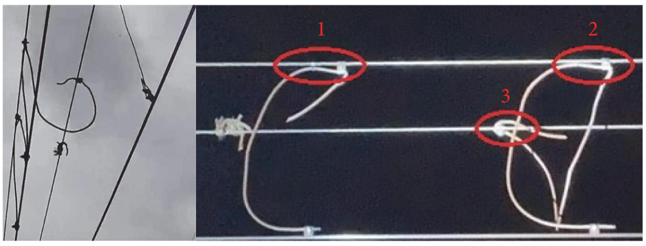


Figure 48: Failed jumper being spotted in pantograph camera footage and then checked on site within 12 hr.

helps the failure's early identification during a ground-level inspection. Finally, if a jumper's leg breaks and falls like the one in Figure 48, it will unlikely affect passing pantographs. However, the electrical continuity is reduced; this may lead to one of the two wires not being sufficiently earthed during overhead line isolation. The jumper needs to be renewed sooner rather than later.

## 6. Maintenance Strategies

Effective maintenance has been a key to the railway's high-performing operation. The railway's maintenance strategy currently is a mixture of reactive correction (failure repair), schedule-based prevention, and discontinuous condition monitoring ("snapshots"). This section introduces the common practices of rectifying dropper and jumper failure as well as the scheduling principles and proactive planning of overhead line maintenance. It then discusses how to improve maintenance effectiveness, cost-efficiency, and safety, based on failure deterioration, analysis of maintenance records and practices, and advanced onboard camera technologies.

Network Rail is the infrastructure owner and maintainer of the ECML, and the maintenance practices are derived from its standards—mainly NR/L3/ELP/27237 [50] and NR/L2/ELP/21087 [51]. The overhead line's maintenance working instructions are grouped in NR/L3/ELP/27237; modules NR/OLE B01 and B10 are for general ground-level and high-level inspection, respectively. The frequency of each inspection is recommended in Appendix B of NR/L2/ELP/21087, while the failure modes and their repair timescales are in Appendix C. In case the deadline of a repair or inspection is missed, the standard's Appendices E1, E2, E3, …, E6 offer guidance flow charts to reschedule the maintenance activity.

*6.1. Failure Repair.* The installation and removal of a "key" clip dropper can be completed on the ground by a set of live line dropper tools on the end of insulated poles (Figure 49) or at a high level with staff in the basket of a MEWP (Figure 50) with the overhead line being earthed. The former is often considered a temporary repair. A black or red plastic tag is usually attached to the middle of the dropper's wire to ease the installation. This can be used as a reminder of the droppers being replaced in this way. When the time of track access is insufficient for repair, staff may cut away the bottom

Figure 49: Staff installing a rigid stainless steel dropper on the ground that the left staff is installing while the right staff is pushing up the wire.

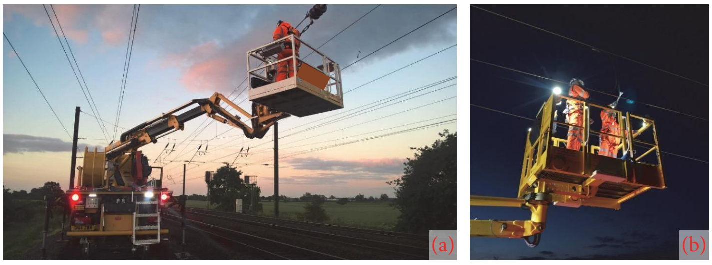


Figure 50: Staff repairing droppers at high-level: (a) installing new dropper and (b) repositioning shifted dropper.

half of the droppers in failure mode 1b (Figure 16) and 1d (Figure 18) using a live line cutter, making the droppers like the ones in Figure 22(b)–22(d), to avoid them hitting passing pantographs. The temporarily repaired droppers are renewed later by staff in a MEWP. The renewal is usually scheduled for within a year. Bolted clips are more difficult to replace from the ground via live line tools than "key" clips. The replacement is nearly always carried out with the use of a MEWP, with more maintenance cost and less planning flexibility. When more than two droppers are detached, the overhead line's weight may exceed the staff's ability to raise on the ground by insulated poles, and therefore a MEWP is usually required.

During high-level maintenance, staff knock shifted droppers back to their upright position (Figure 50(b)). In addition, staff may release a dropper's vertical tension by manually lifting the contact wire slightly to check the cam lock's tightness. The cam lock is renewed when it can be moved along the contact wire freely.

*6.2. Schedule-Based Failure Prevention and Proactive Planning.* Dropper and jumper failures are generally not instantaneously disruptive; a block to pantographs' passing normally follows a period of deterioration. Preventive maintenance is predominately schedule-based in the area of this study. It includes non-disruptive ground-level inspection and cab rides to spot the failures and disruptive major overhauls to fully rectify them. The overhauls are planned based on wire runs. For example, in Figure 51, a failure being identified in the 1st patrol could be prevented from significantly disrupting the railway's operation if either the major overhaul's frequency was doubled to rectify the failure earlier or special arrangements (e.g., restricting the speed to 100 mph or lower, coasting over a short distance, and temporarily removing a failed dropper or jumper) were implemented to slow down the deterioration for the failure to be repaired in the next scheduled overhaul. Doubling the maintenance frequency notably incurs extra maintenance costs, and the special arrangements are usually unplanned and affect the normal railway's operation [52].

Maintenance staff can plan inspection every 12 weeks, a cab ride every week, and overhaul every 4 years where the speed is more than 100 mph or 6 years where the speed is less (although nearly all of the dropper failures occur on the fast lines, the slow railway lines are mentioned here because they are next to the fast lines on the ECML and the planned access on slow lines can sometimes be amended at short notice and used to rectify the droppers on their adjacent fast lines). Each ground-level inspection may cover 2–6 km, depending on signalling capacity and access availability, and the majority of the inspections may be carried out at night to minimise the impact on train operations. Overhauls may need to be planned half a year in advance; access involves earthing the overhead line equipment, which is much more complicated and time-consuming than access for ground-level inspection. In such a situation, overhauls can be scheduled and distributed evenly on the time and the geographical horizon (Figure 52) so that when an urgent dropper or jumper failure is identified, instead of staff

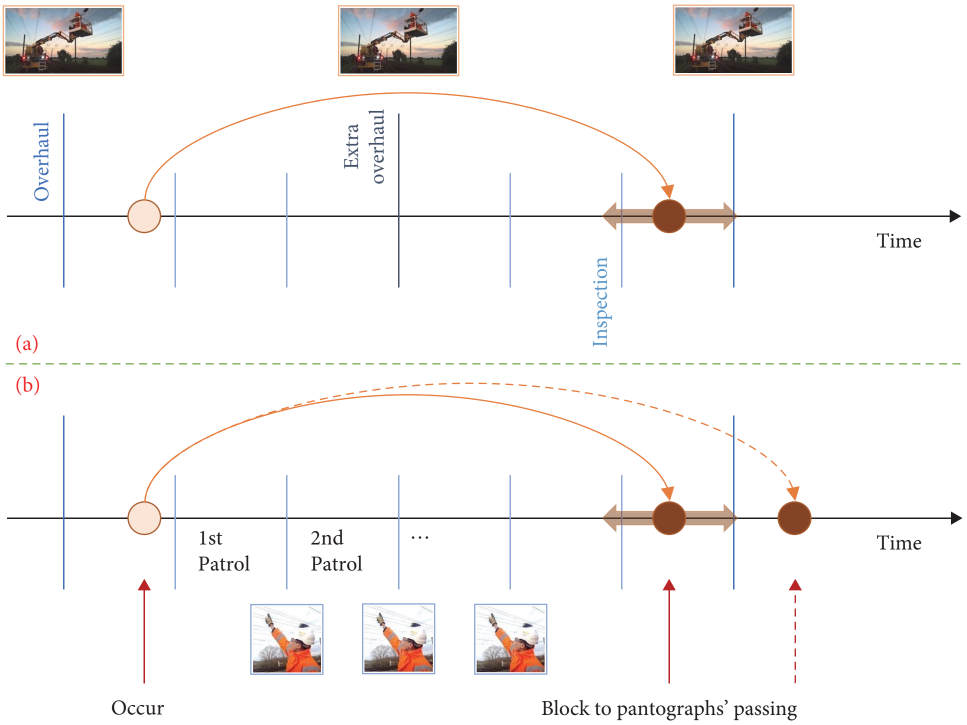


Figure 51: Prevent failure causing significant service disruptions in schedule-based maintenance: (a) double the overhaul's frequency to repair the failure earlier and (b) implement special arrangements to slow down the deterioration.

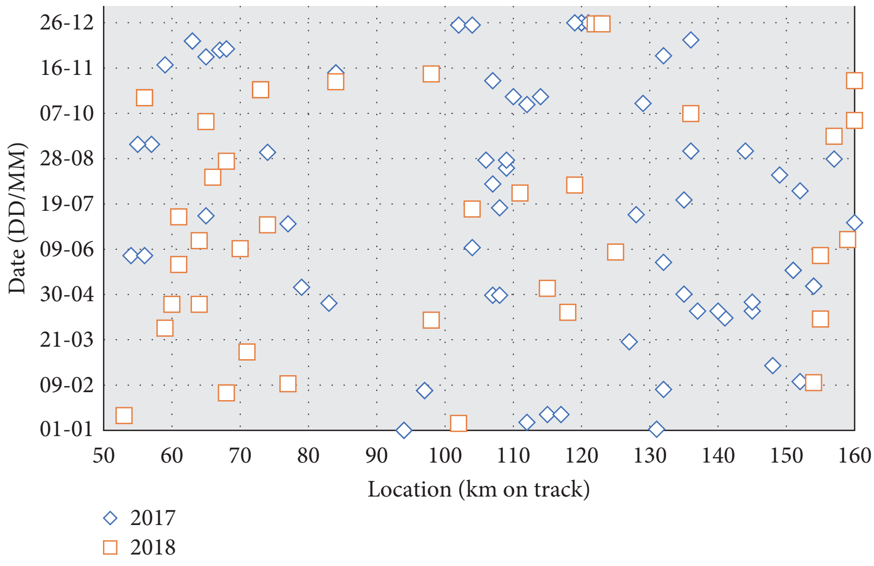


Figure 52: Overhauls are scheduled and distributed evenly on the time and geographical horizon, 2017 and 2018's maintenance records.

applying for disruptive emergency access, the boundary of each overhaul's worksite can be fine-tuned to accommodate last-minute rectification, so any special arrangements may be implemented for a minimum duration.

*6.3. Deterioration and Early Intervention.* The four main stages of dropper condition deterioration are summarised in Figure 53; a kinked or shifted dropper detaches or breaks (or goes missing) and then affects adjacent droppers if the risk is not addressed promptly. As mentioned previously, three out of the four stages require emergency response, with insufficient time and flexibility for maintenance staff to prepare and to plan the job. The rectification timescale jumps suddenly from 4 years to 7 days. An intermediate stage, droppers coming off, can be inserted between stages 0 and 1 as a non-standard approach to slightly smooth out the urgency, with its repair timescale being, for example, 3 months. A similar situation applies to jumpers.

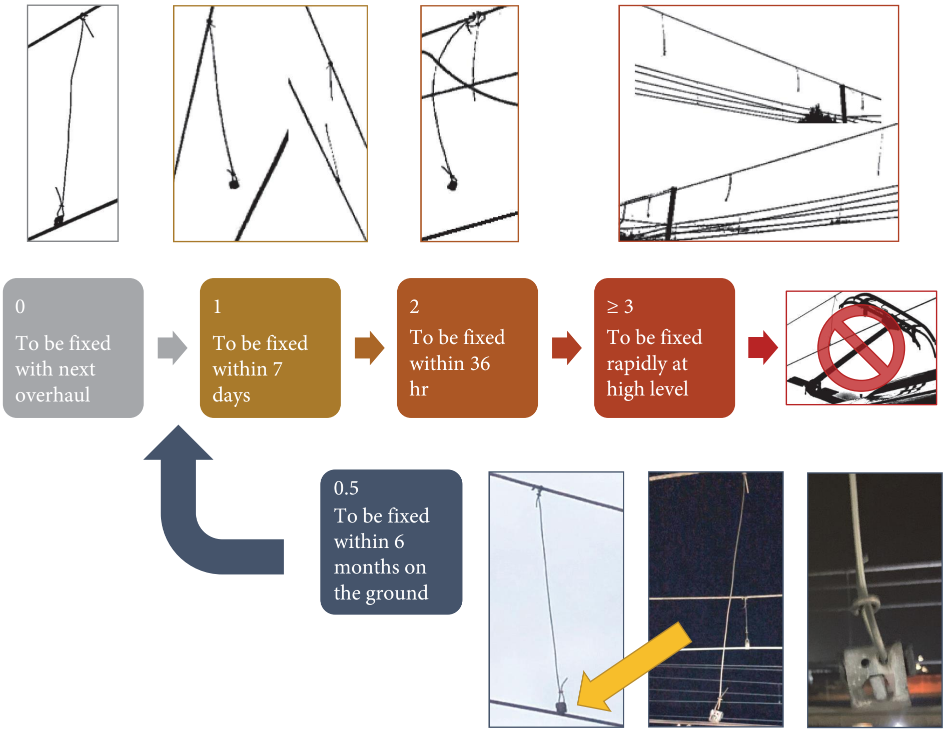


Figure 53: Four main stages of droppers' condition deterioration and the additional non-standard coming-off stage.

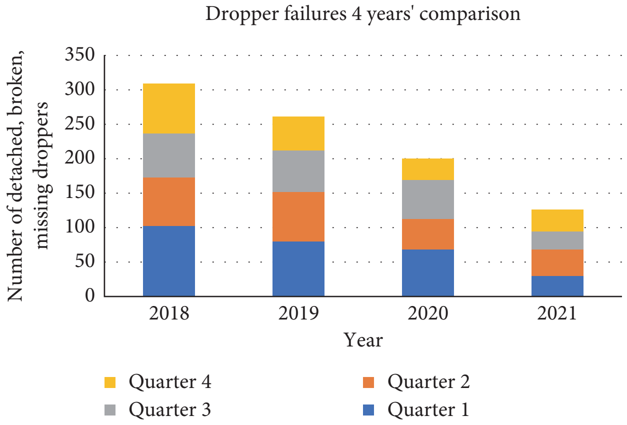


Figure 54: Annual total number of detached, broken, missing droppers from 2018 to 2021.

Signs of a dropper coming off are identifiable during a ground-level inspection, and temporary replacement on the ground or early renewal in the basket of a MEWP can be carried out within the timescale in planned access. With this stage being introduced, the need for emergency access to fix dropper failures in the 7-day timescale can be eased slightly; maintenance staff can gain more flexibility in resource planning and better prevent pantographs from being chipped or severely damaged by failed droppers. However, in the 4 years' data, despite 24% of the 135 "coming off" droppers deteriorating to the next state within a year, the majority—128 of them—were assigned a rectification timescale of 2 years. It is important to formalise this state as a standard failure mode and assign a suitable and affordable rectification timescale to it.

In addition to continuous improvement in maintenance strategy, since 2016, funding has been allocated every year for the droppers' and jumpers' mass renewal. Both measures together have successfully driven the occurrence of detached, broken, and missing droppers from an average of six per week in 2018 to two per week in 2021 in the studied railway patch—the ECML between Cambridge Junction and Stoke Junction (Figure 54).

*6.4. Quality Control.* In the 4 years, ~17% of the 893 detached, broken, or missing droppers failed again after repair, and more than half of the repetitive failures occurred within half a year of repair. The repetitive failures' occurrence versus time to repair histogram (Figure 55) shows a pattern of exponential distribution when the failures are

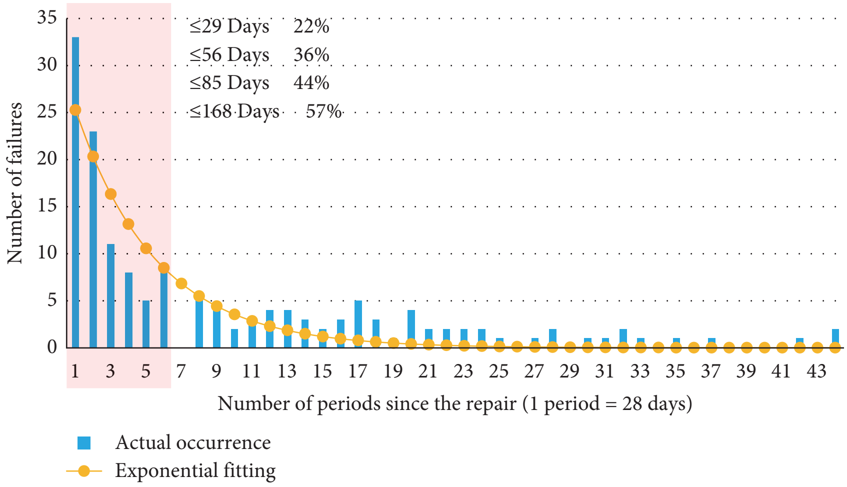


FIGURE 55: Histogram of the time after which repaired droppers fail again.

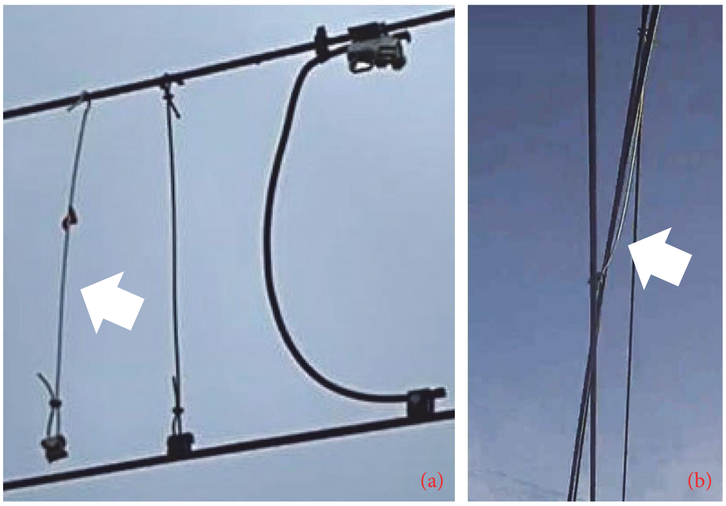


FIGURE 56: Substandard dropper installations: (a) uninstalled dropper being left on wire and (b) dropper rubbing crossing wire.

binned together every 28 days. Most of the recurrences are within the first year, and it is more important in practice to understand their initial surge than their distribution's long tail of low likelihood. The first year's data is used for an exponential distribution fit. Chi-square distribution is used for assessing the goodness of fit. The fitting result is $f(t) = 1/4.5862 \times e^{(22.7966 - t/4.5862)}$, with sufficient confidence based on the significance level at 0.05.

The data indicate potential issues of workmanship and ergonomics. Another two examples of substandard dropper installation are shown in Figure 56. A redundant dropper was not removed in Figure 56(a). The dropper and the crossing overhead line wire were touching each other in Figure 56(b), so the position of the dropper needed to be reconsidered. It is important to double-check the repair shortly afterwards, and this is another factor to be considered when engineers plan a ground-level inspection, especially where access to track is challenging.

*6.5. Onboard Cameras for Condition Monitoring.* Since 2017 reviewing pantograph camera footage has gradually become the "new normal" of the ECML overhead line equipment maintenance. Since 2021 fresh footage has been available every week. Two significant benefits of the footage are (a) engineers being able to identify a failure in between any two scheduled ground-level inspections easier than cab rides, as the footage can be played at a reduced speed and paused to review any failures more thoroughly; and (b) the overhead line equipment's dynamic performance being recorded for risk assessments and future comparisons. To manage the quality of maintenance work, onboard camera footage can be used to check a dropper's condition, e.g., 3 months after a repair. This reduces the need for staff walking on track and greatly improves track workforce safety. Similar solutions have been applied to maintaining the high-speed railway in China since 2013. Any abnormalities such as contact wire irregularities and loss-of-contact arcing are addressed promptly, and the equipment's annual failure rate has been successfully managed from 1.3 per 100 km railway in 2013 down to 0.42 in 2019 [23]. It is important that engineers continuously utilise advanced sensing and telecommunication technologies to better monitor the condition of the infrastructure and continue to digest existing data and maintenance records to improve their practice.

## 7. Conclusions and Future Works

Droppers and jumpers are large-volume components on the British ECML and critical for maintaining its overhead lines' designed position so pantographs can pass smoothly and collect electricity stably. To provide frequent and punctual train services, the industry is faced with less frequent and shorter maintenance windows but higher expectations on its maintenance's performance. This paper aims at applying modern maintenance and reliability theories, together with an analysis of maintenance records and references to veterans' expertise, to make the maintenance more accurate and efficient. It systematically documents dropper and jumper strengths and weaknesses and offers an insight to improve dropper and jumper design for the railway overhead line contact system's safe and high-performing operation.

FMEA has been demonstrated in this paper as an effective tool in supporting the maintenance of railway overhead line equipment. It is a systematic approach that helps engineers thoroughly study the rates and causes of failure and its potential disruption to the railway's normal service. With sufficient and detailed data, domain expertise, and the successful application of FMEA, engineers are able to understand the details of dropper and jumper failure modes and to produce an appropriate plan for their routine maintenance and emergency response. This paper follows the FMEA framework and reflects on 4 years' real-world maintenance records. It analyses failure occurrence, deterioration, identification, rectification, and prevention, and its disruption to train services. Each failure's deterioration is also considered together with the challenges of track access in scheduling routine maintenance activities and proactively being ready for emergency repair. The outcome of the analysis recommends three directions to improve the overhead line contact system's operational performance.

1. Unlock the potential benefits of proactive planning for short-notice failure rectification to achieve less service disruptions.
2. Standardise an extra failure mode—droppers and jumpers coming off—to support the early identification and control of the components' condition deterioration.
3. Carry out after-action checks to identify substandard repairs and prevent failure recurrence.

The results are presented concisely to provide guidance for maintenance engineers to develop appropriate strategies to address the risk of various failure modes. They also suggest that effective quality control measures and novel technologies in monitoring the equipment's operating condition are promising solutions and necessary responses to emerging challenges.

Future research on this topic could focus on three main aspects. (a) Explore the use of computer software in depth—including the deep learning capacity of artificial intelligence and techniques of data mining—to automatically review maintenance records, and digest the large volume of condition monitoring data, to pave the way towards decentralised, closed-loop, and intelligent maintenance decision-making. (b) Study the impact of overhead line geometry on the dropper failure modes' rate of occurrence and tailor the maintenance plan to minimise the per-unit operating expense and loss-of-service cost. (c) Research failure deterioration probability and component reliability.

## Data Availability

The (railway operation and maintenance) data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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