Rail Accident Investigation Branch

Rail Accident Report

Detachment of a cardan shaft at Durham station
10 April 2011

Department for Transport

Report 12/2012
July 2012

This investigation was carried out in accordance with:

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

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Detachment of a cardan shaft at Durham station 10 April 2011

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Summary

On 10 April 2011, at around 12:30 hrs, a cardan shaft fell from an empty class 142 passenger train travelling through Durham station at 75 mph (120 km/h). The train ran for a distance of approximately 2 miles (3.2 km) before being stopped. A member of the public standing on a platform suffered a minor injury from ballast thrown up as the cardan shaft fell onto the track; the train suffered damage, including loss of diesel fuel.

The immediate cause of the detachment was the complete fracture of a final drive input shaft. The input shaft fractured because a seized input bearing generated a large amount of frictional heat between the shaft and bearing. The input shaft was locally heated to a temperature at which its strength was reduced so that it could no longer carry its normal loading.

The RAIB established that the seizure of the bearing was due to the setup of the bearings during overhaul which resulted in a lack of end float in the bearings when in operation. The final drive failure was not detected by the checks which were in place to identify the onset of such failures. The detached cardan shaft was not retained by its safety loops.

The RAIB has made six recommendations to Northern Rail and owners of class 14x vehicles. Two recommendations relate to reviewing the end float and alignment requirements for the class 14x final drives and ensuring that any changes to the setup of safety critical components are validated. One recommendation covers the detection of impending final drive failures. The fourth recommendation relates to the final drive post-overhaul testing and the fifth covers the provision of key design information to overhaul and maintenance contractors. The final recommendation relates to the completion of the review work associated with the events in the immediate aftermath of the accident.

Introduction

Preface

1 The sole purpose of a Rail Accident Investigation Branch (RAIB) investigation is to prevent future accidents and incidents and improve railway safety.

2 The RAIB does not establish blame or liability, nor carry out prosecutions.

Key definitions

3 The report contains abbreviations and technical terms (shown in *italics* the first time they appear in the report). These are explained in appendices A and B.

4 All dimensions in this report are given in metric units, except speed and locations which are given in imperial units, in accordance with normal railway practice. Where appropriate the equivalent metric value is also given.

5 All distances recorded in miles in this report are measured from a 'zero' datum at York station.

6 References to 'inner' and 'outer' bearings are made in this report; inner bearings are those nearest to the centre line of the *wheelset*. References to the 'inner' and 'outer' *ring* of a bearing are made relative to the shaft on which the bearing is fitted; inner rings are those nearest to the centre line of the shaft.

7 The family of diesel multiple units of classes 142, 143 and 144, known as 'Pacers' is referred to generally as class 14x in this report. Class 14x *final drives* are referred to by their unique reference number assigned by the original manufacturer which takes the form of 'UTxxxx' where xxxx represents a four-digit number. For example, the final drive involved in this accident is referred to as 'UT1140'.

The accident

Summary of the accident

8 At 12:29 hrs on Sunday 10 April 2011, train 5G01, a northbound empty passenger train was travelling through Durham station at 75 mph (120 km/h) when one of its final drive *cardan shafts* dropped onto the track. Train 5G01 was the 10:36 hrs Neville Hill depot, Leeds to Heaton depot, Newcastle-upon-Tyne. During the incident, a member of the public standing on a platform at the station sustained a minor injury from a piece of *ballast* thrown up by the broken shaft.

Figure 1: Unit 142045 at Heaton depot on 11 April 2011

9 The train involved was formed of two 2-car class 142 units (figure 1). The shaft detached at the trailing end of the third vehicle and was not held up by its *retention devices* (in this case two *safety loops* – figure 3). The detached cardan shaft came to rest between the rails of an adjacent line after damaging the underside of the third and fourth vehicles, piercing the fuel tank on the fourth vehicle and releasing around 500 litres of diesel fuel onto the railway.

10 Unaware of what had occurred, but alerted by an un-commanded brake application and the engine warning light illuminating on his cab console, the driver stopped his train on the approach to signal T291, 2 miles (3.2 km) outside Durham station (figure 2).

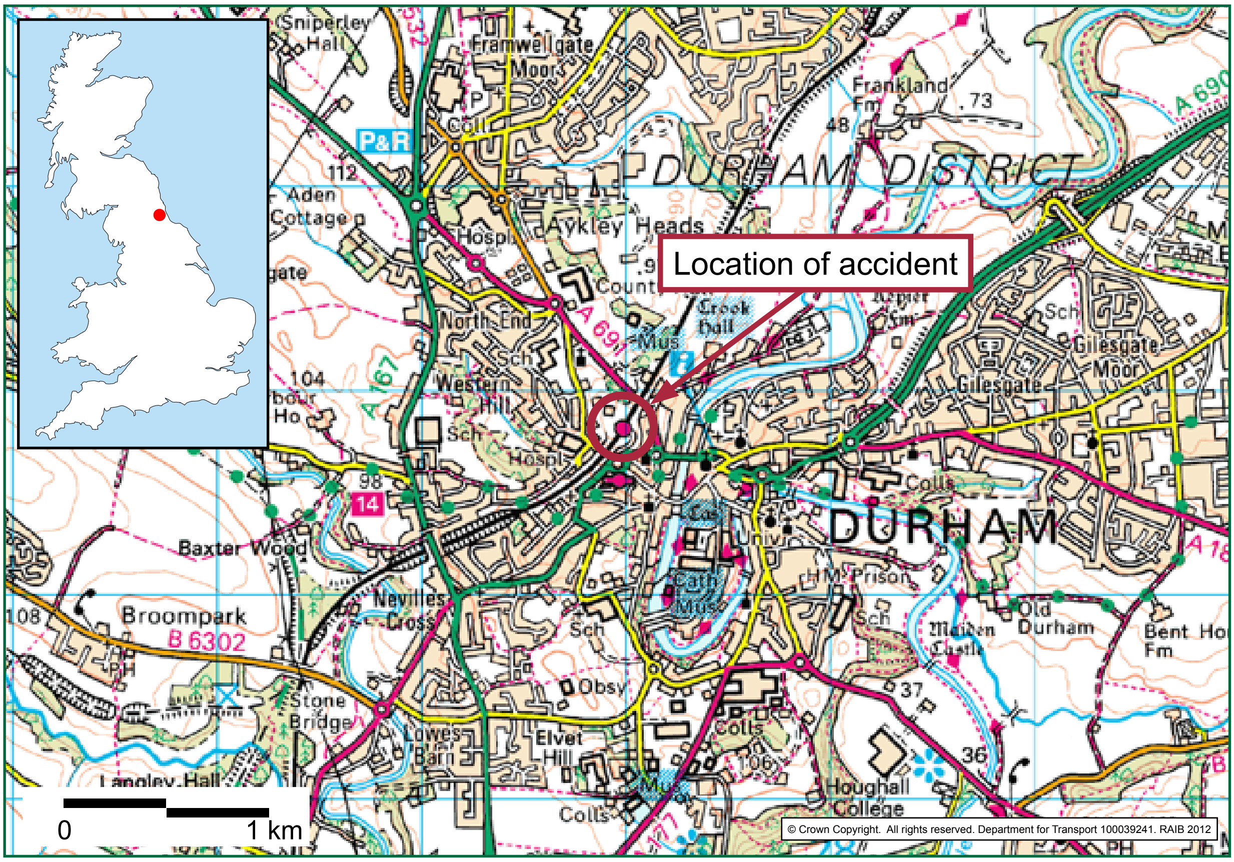


Figure 2: Extract from Ordnance Survey map showing location of accident

11 The driver examined his train and isolated the rearmost two engines, one of the *main reservoirs* and an air-pressured toilet header tank with a dislodged air supply pipe. This enabled him to rebuild air pressure in his train to release the brakes.

12 At 13:21 hrs, train 5G01 restarted its journey towards Newcastle with the cardan shaft missing. The line was re-opened at 13:24 hrs.

Context

Location

13 Durham station is located at 66 miles and 13 *chains* on the East Coast Main Line (ECML) between Darlington and Newcastle.

14 The railway through Durham station consists of three tracks: the *up main*, *down main* and *down slow* lines. The up main and down slow lines serve the two platforms at Durham station and the down main line is a through route. Train 5G01 was travelling on the down main line. The maximum permissible speed on the down main line is 75 mph (120 km/h) on the approach to the station changing to 90 mph (145 km/h) through the station at 66 miles 14 chains. In the direction of travel of train 5G01, the track is on a gentle 1 in 120 down gradient.

15 Train movements are controlled by *four-aspect colour light signals* operated from Tyneside Signalling Control Centre (SCC). The track is electrified with 25 kV AC Overhead Line Equipment but the train was running under its own diesel power.

Organisations involved

16 Train 5G01 was operated by Northern Rail, who also employed the driver.

17 The track and signalling infrastructure of the ECML are owned, operated and maintained by Network Rail.

18 The train was owned by Angel Trains, who leased the train to Northern Rail. Porterbrook owns some class 143 and 144 vehicles which have the same final drive arrangements. Porterbrook also took part in this investigation.

19 Angel Trains commissioned Unipart Rail (formerly Railpart) as the overhaul contractor for the class 142 final drives.

20 In turn, Unipart Rail engaged a *Technical Engineering Service Company* (TESCO) to prepare an overhaul instruction for the class 142 final drives and commissioned LH Group to overhaul the class 142 final drives. LH Group also overhauls the Porterbrook owned class 143 and 144 final drives. All this work is carried out at its facilities in Barton-under-Needwood, Staffordshire.

21 The *input bearings* of the final drive were supplied by Timken.

22 All parties freely co-operated with the RAIB investigation and provided assistance during the course of this investigation.

Staff involved

23 The driver of train 5G01 qualified as a driver with Northern Rail in September 2005. He is qualified to drive class 14x and 15x units and has a good performance history.

Train involved

24 The train was made up of unit numbers 142020 (leading) and 142045 (trailing). The detached cardan shaft had been fitted to vehicle 55636 of unit 142045 (the third vehicle in the train in the direction of travel).

25 Class 142 units were first introduced from 1985 to 1987 by British Rail and were designed by British Rail Engineering Ltd (BREL) and Leyland to operate at a maximum speed of 75 mph (120 km/h).

26 Class 142 units normally operate in single unit formations but may also operate in multiple with both class 14x and 15x units (class 15x includes classes 150, 153, 155, 156, 158 and 159).

Rail equipment/systems involved

27 Class 142 units were originally delivered with TL11 engines manufactured by Leyland. The company Self Changing Gears (SCG) manufactured the gearboxes and final drives. However, by 1991, the SCG gearboxes proved unreliable and were replaced with Voith T211r gearboxes. Class 142 units were also re-engined with Cummins LTA10 engines between 1994 and 1996. The final drives remain to the original SCG design. Class 143 and 144 units were built by other manufacturers but use the same final drives.

28 The Voith gearbox is connected to the axle mounted SCG final drive by a long cardan shaft (figure 3). To reduce the risk associated with a detached cardan shaft, two body mounted safety loops are located around the cardan shaft. In order to accommodate the cardan shaft movement during normal operation, a gap exists between the safety loops and the cardan shaft.

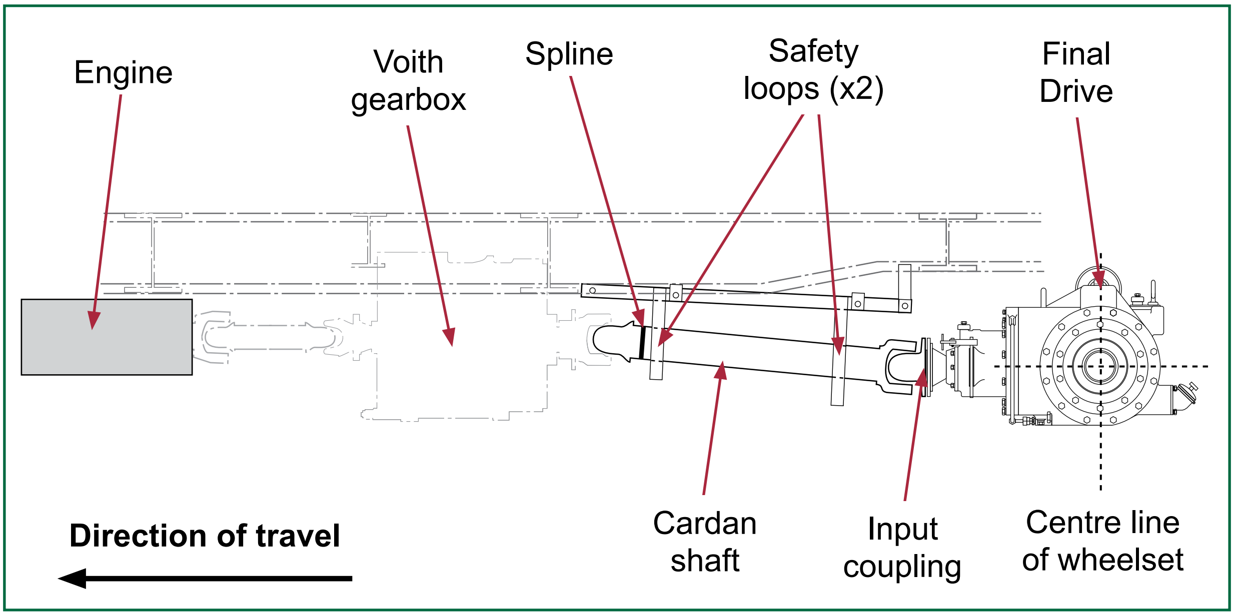


Figure 3: Drive arrangement on Class 14x

29 The SCG final drive, model RF420i, is a *single reduction bevel gearbox*. It is connected to the cardan shaft through an input coupling which drives the input shaft within the final drive (figure 4). Power is transmitted by the input shaft to the pinion shaft which in turn drives the wheelset through a set of bevel gears (figure 4). The final drive is oil lubricated and oil cooled with the oil pump being mechanically driven directly off the axle.

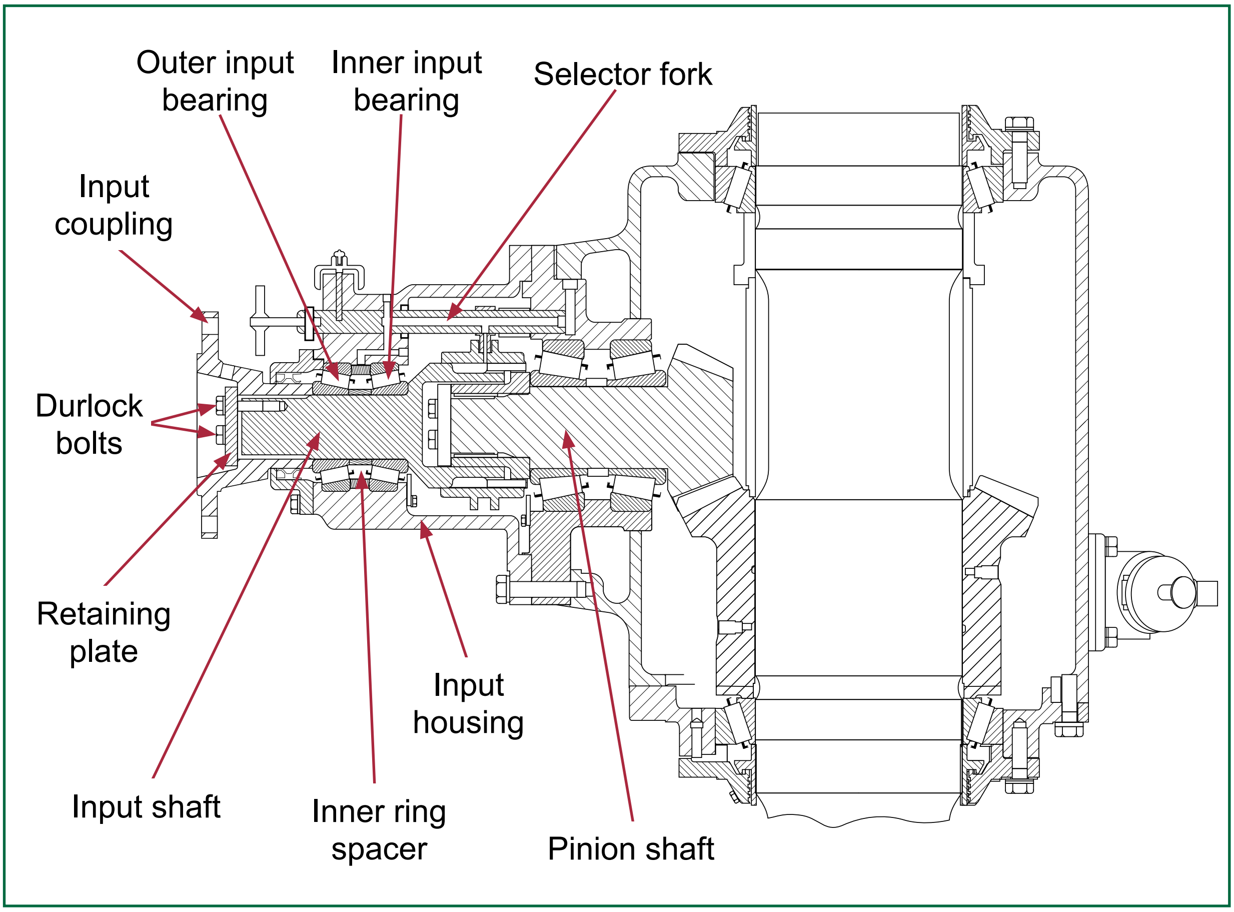


Figure 4: Final drive cross-section

30 The input shaft and pinion shaft incorporate a clutch device so that the drive can be manually isolated. This isolation device, known as the selector fork, was rarely used and troublesome. As a result, in the early years a modification was implemented on all final drives to include a pin to permanently lock the selector fork in position. The final drive fitted to vehicle 55636 of unit 142045 was fitted with this modification.

31 Although not relevant to this accident, a further modification programme is now underway to eliminate the selector fork (paragraph 69).

32 The input shaft is mounted within the final drive input housing through a pair of *tapered roller bearings* (figure 5 shows the various bearing components). These bearings, referred to in this report as the input bearings, are mounted *back-to-back*. The inner rings of the bearings together with the inner spacer ring are clamped in between the input coupling and input shaft by the retaining plate and *Durlock* bolts.

33 Bearings produce heat when in normal operation and the inner ring of a bearing usually runs hotter than the outer ring. This is because the outer ring is usually in direct contact with the air cooled housing whereas the inner ring is in contact with a shaft that is less able to dissipate the heat transferred to it. This temperature difference between inner and outer rings causes the inner ring to expand more than the outer ring when running. To accommodate this differential expansion the bearing is set up at installation with a radial clearance. The radial clearance is defined as the radial gap between the rollers and the outer ring once installed (figure 5). On tapered roller bearings, the radial clearance is directly related to the axial clearance also known as 'end float'.

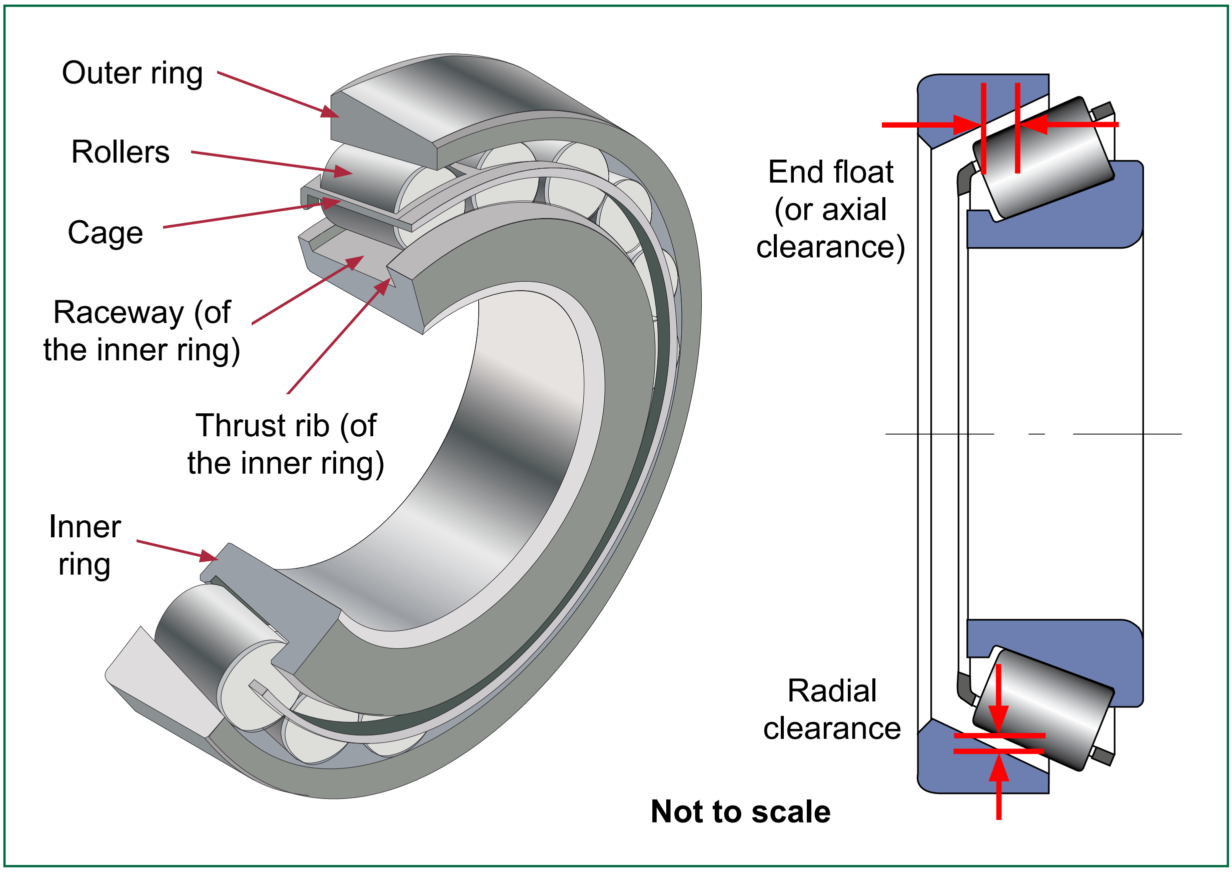


Figure 5: Tapered roller bearing

34 The optimum running condition for a tapered roller bearing is when the axial and hence radial clearance is zero. When there is insufficient axial clearance the bearing can become *preloaded*.

35 It is possible to run bearings with a small preload. However, this is a sensitive condition. Preloading a bearing too much can result in large internally generated loads which in turn generate frictional heat. In oil cooled bearings, the heat generated within the bearing is normally dissipated by the oil. However, the oil also has a lubricating function: it reduces friction by separating the moving components with a thin lubricating film. As the bearing runs hotter, the viscosity of the oil decreases reducing its ability to maintain the lubricating film. Above a certain temperature and regardless of the amount of oil supplied to the bearing, the oil film will be too thin to prevent metal-to-metal contact, friction and then heat will build up rapidly. If not stopped quickly a chain reaction is started, the temperature will rise rapidly and the bearing will fail in a catastrophic manner; this is known as a thermal runaway.

External circumstances

36 On 10 April 2011 in Durham, the weather was dry with clear skies. The ambient temperature around midday was 19°C and the wind speed was low at 1.5 m/s.

37 The external circumstances did not affect the accident.

Events preceding the accident

38 On 8 December 2010, final drive UT1140 was removed from vehicle 55721 of unit 142071 for its mileage-based overhaul at LH's facility in Barton-under-Needwood. UT1140 had covered 184,050 miles since its last overhaul in March 2009 at the same facility. The actual overhaul of UT1140 by LH did not start until 14 February 2011 and was completed by 17 February 2011. On 23 February 2011, final drive UT1140 was fitted to vehicle 55636 of unit 142045 by Northern Rail's maintenance staff at Newton Heath depot.

39 Four days previously on 19 February 2011 and following a recent series of final drive incidents involving failed input bearings (paragraph 71), Northern Rail introduced a regime of regular fleet-wide lift checks on the class 14x final drives (paragraph 73). The checks were carried out at least every three days and were looking to identify a lift of 1 mm or more at the input coupling which would indicate the onset of an input bearing failure. The lift checks were Northern Rail's chosen measure to control the risks associated with final drive failures. As a unit which had covered less than 12,000 miles since its last final drive replacement, unit 142045 was included in this programme.

40 On 17 March 2011, unit 142045 was subjected to its last routine maintenance examination before the accident. During this visual examination, the final drive oil level was checked and found to be normal.

41 On 8 April 2011, at Newton Heath depot, Northern Rail depot staff carried out the last lift check before the accident on unit 142045. The fitter who carried out the check stated he did not notice anything of concern with UT1140.

42 On 9 April 2011, unit 142045 completed two passenger carrying journeys covering 543 miles before being taken out of service for a major pre-planned and routine overhaul. At the end of this day, unit 142045 was stabled at Neville Hill depot in Leeds before being moved the next day to Heaton depot in Newcastle for the overhaul.

43 At around 10:30 hrs on 10 April 2011, unit 142045, coupled to unit 142020, started its journey from Neville Hill to Heaton. The initial leg of the journey was a short trip to Leeds station during which units 142045 and 142020 were also coupled up to unit 158859. At Leeds station, unit 158859 was uncoupled.

44 It was also at Leeds station that the driver of train 5G01 took charge of the train. He had previously booked on duty at 09:00 hrs. He spoke briefly to the Leeds driver that he relieved and confirmed that there were no problems with the train.

45 At 10:41 hrs, train 5G01 left Leeds station and travelled initially to York station, where it arrived at 11:09 hrs after 28 minutes of continuous running at speeds between 30 and 75 mph (50 and 120 km/h). Train 5G01 was detained in platform 11 of York station for eight minutes to allow another train to run in front of it.

46 At 11:17 hrs, train 5G01 left York and travelled to Darlington, where it arrived at 11:55 hrs after 38 minutes of continuous running at maximum speed. Train 5G01 was then detained on the down passenger *loop* outside Darlington station for 11 minutes to allow other trains to pass it.

47 At 12:06 hrs, train 5G01 left Darlington heading towards Newcastle.

48 At 12:29 hrs, train 5G01 entered Durham station travelling at maximum speed on the down main line.

Events during the accident

49 At 12:29 hrs, as train 5G01 was passing through Durham station, the cardan shaft of vehicle 55636 dropped from the rear of the train causing a shower of ballast and a cloud of smoke. The detached cardan shaft came to rest in the *four-foot* of the up main line, within the confines of the station. A member of the public standing on platform 1 adjacent to the up main line received a minor injury after being struck by a piece of ballast.

50 The station staff immediately contacted the signaller at Tyneside SCC to report the accident. The signaller advised the station staff that he would contact the driver of train 5G01 to ask him to stop and examine his train.

51 Approximately 80 seconds after the detachment of the cardan shaft and while the station staff was on the phone to the signaller, the driver of train 5G01 experienced an unexpected brake application. At the same time, he noticed that the engine light on his cab console had illuminated and that the main reservoir pressure gauge was dropping rapidly, indicating that air was leaking from the air system on his train.

52 It took approximately 40 seconds for the train to come to a stop which is typical from the speed (approximately 75 mph (120 km/h)) for this class of vehicle. By that time, it was 2 miles (3.2 km) north of Durham station standing at signal T291 (68 miles 15 chains). It was now 12:31 hrs.

Events following the accident

53 Using the *signal post telephone* at signal T291, the driver of train 5G01 immediately contacted the signaller at Tyneside SCC, who had just finished speaking to the station staff. The driver informed the signaller of the unexpected brake application. In response the signaller informed the driver of the initial station staff report (paragraph 50). The driver and the signaller agreed that the driver would go and examine his train and report back to the signaller.

54 As the driver was examining his train, the station staff contacted the signaller again to report that a large cardan shaft had been found in the four-foot of the up main line (figure 6 shows the recovered shaft). The signaller blocked the up main line to all traffic, the down main line already being blocked by the stationary train 5G01. The signaller then told the driver that a cardan shaft had been found on the track at Durham station.

55 The member of the public who had been injured received first aid treatment from the station staff. Staff offered to call an ambulance, but the member of the public declined this. The station staff also noted the details of the damage from the flying ballast to two cars parked at the station.

56 During his examination, the driver identified that one of the fuel tanks had been pierced and that air was leaking from his train (paragraph 11). The driver contacted Northern Rail's control at York to seek advice. With the guidance of the maintenance controller through several telephone conversations, he identified which cardan shaft was missing, isolated the two engines on unit 142045, and the main reservoir and air supply to the toilet module on the rearmost vehicle. The driver was then able to slowly rebuild the air pressure in the train necessary to release the brakes.

57 In the meantime, approximately 500 litres of diesel fuel leaked onto the railway from the pierced fuel tank.

58 Having built up enough air pressure in the train's air system to enable the release of its brakes, the driver contacted the signaller. The driver requested a clear run to Newcastle as he was concerned about the time it would take him to re-build air pressure if he had to stop his train anywhere along the way. He was also aware that traffic was backing up on the ECML.

59 Train 5G01 departed from signal T291 at 13:21 hrs and reached Newcastle at 13:33 hrs. The train achieved a maximum speed of 75 mph (120 km/h) on this journey.

60 Network Rail contacted the Environmental Agency at 13:10 hrs to report the diesel spillage. Network Rail also organised a clean up contractor to attend the site, as an amount of diesel had collected in a gully adjacent to the line at a point where a nature reserve was sited on the opposite side of the line.

Figure 6: Recovered cardan shaft

The investigation

Sources of evidence

61 The following sources of evidence were used:

- witness statements;
- data from the *on-train data recorder* (OTDR);
- *Control Centre of the Future* (CCF) replay;
- Closed circuit television (CCTV) recordings taken from Durham station;
- records of communications between the driver, the signaller and the maintenance controller;
- findings from the controlled disassembly of failed final drives;
- site photographs and measurements;
- weather reports and observations at the site;
- a metallurgical examination report commissioned by the RAIB;
- a review of other final drive incidents and associated technical reports;
- LH drawings and overhaul procedures (WI-27, CR/CI0590);
- LH build records;
- historical overhaul procedure (WOSS 240/3);
- SCG drawings and original product manual;
- a bearing expert report commissioned by the industry including the output of bench tests; and
- a review of previous RAIB investigations that had relevance to this accident.

Key facts and analysis

Background information

62 Following the introduction of class 142 into service in 1985-1987, the final drives were initially overhauled by the original manufacturer, SCG. After Cummins UK sold SCG to Alvis Rail in 1989, the overhaul of the final drives moved to Alvis Rail from 1989 to 1997. David Brown bought Alvis Rail in February 1998 and for a short period overhauled all class 14x final drives through one of its companies, Hygate Transmission.

63 In early 1999, the contract for the overhaul of the class 14x final drives was due for renewal. This contract was managed at the time by Railpart on behalf of Angel Trains and Porterbrook. Railpart awarded the new contract to LH. Around mid-1999, Railpart commissioned a TESCO to produce a new working instruction for LH (WI-27) to cover the overhaul of the class 14x final drives because neither Railpart nor LH had access to the original design and overhaul documentation for the final drives.

64 The TESCO used an existing British Rail document, Workshop Overhaul Standard Specification (WOSS) 240/3 to prepare LH's working instruction, WI-27. This WOSS, entitled 'Self Changing Gears RF42i and RF420i Final Drive', was first published in May 1985. Despite its title suggesting that it covered RF420i final drives, WOSS 240/3 only covered the RF42i final drives, which were of a different design. The TESCO adapted WOSS 240/3 with the aim of making it applicable to the RF420i final drives.

65 After a period during which WI-27 was revised several times as a result of production experience gathered by LH, LH started overhauling the class 14x final drives in earnest in March 2000.

66 In 2000, when faced with the need to replace some of the final drive parts without having any original design information, LH started re-creating a full set of drawings for each individual part using measurements derived from actual components (this is sometimes described as 'reverse engineering').

67 By mid-2001, and following a number of final drive incidents associated with bearing outer rings slipping inside the input housing, WI-27 was again modified to alter the fit between the outer ring and input housing. This modification was implemented in November 2001. This was the last known modification to WI-27 for more than 7 years before January 2009 when the fit between the outer ring and input housing was again modified with the introduction by LH of Engineering Directive, GS090 following production issues found during the final drive assembly.

68 In February 2004, Porterbrook commissioned another TESCO to prepare a new overhaul specification for the class 14x final drives and a new overhaul document, CR/CI0590 was created. The technical content of CR/CI0590 is broadly equivalent to WI-27 in all areas but one (paragraph 136). It was not until February 2010 that CR/CI0590 became the referenced instruction in the contractual documents between LH and its customers. This mandated LH to use CR/CI0590 for the overhaul of the class 14x final drives. However, in practical terms, LH has continued to apply the existing requirements of WI-27, modified by directive GS090, to overhaul the final drives.

69 Although the selector fork had been locked out of use (paragraph 30), failure of the selector fork could still lead to a spontaneous disengagement of the final drive. After a number of selector fork failures between 2004 and 2006, LH developed a modification to the design of the final drive which removed the need for the selector fork. In the new design, the input shaft directly drives the pinion shaft without the need for the selector fork. In 2009 and after an initial two year long trial on one final drive, Porterbrook and Arriva Trains Wales, which also operates class 14x vehicles, accepted the modification. Northern Rail accepted the modification on 11 April 2011. All overhauled final drives were subsequently changed to the modified design.

70 Between March 2000 and April 2011, more than 60 final drive incidents were recorded. Each incident was investigated by the industry to understand the failure mode and likely cause. Several different causes were identified including the Durlock bolts coming loose or bottoming out, the selector fork disengaging spontaneously, the outer ring of the bearings slipping inside the input housing, the input bearings seizing and the driving gears fracturing.

71 Before the accident at Durham, a total of 17 final drive incidents had occurred that featured failed input bearings. Northern Rail had experienced the bulk of the incidents but other train operating companies had also experienced some. Four of these incidents took place between March 2001 and June 2004. Six incidents occurred between November 2007 and February 2009 and the remaining seven between August 2010 and March 2011. Five out of these seventeen incidents have resulted in a cardan shaft becoming detached from its vehicle.

72 The latest series of incidents starting in August 2010 led the industry to assemble a working group with representatives from Northern Rail, Angel Trains, Porterbrook, Unipart, LH and their consultants. This working group was created after an incident at Selby on 19 February 2011 in which final drive UT1231 failed on vehicle 55804 of unit 144004, and the cardan shaft came adrift and dropped onto the track. This was the fifth incident in the latest series.

73 The first action that the working group took was to put in place lift checks aimed at detecting impending final drive failures. These lift checks were based on the methodology developed back in 2001 when the industry dealt with the issue of spinning outer rings (paragraph 67). The checks were put in place on 19 February 2011. The following day, final drive UT1090 fitted to vehicle 55757 of unit 142061 was identified as a suspect drive with high lift readings. Upon disassembly, it was found that the input bearings had failed with the outer ring of the outer bearing found loose within the input housing. The cages of both input bearings had disintegrated.

74 A second suspect final drive was identified by the lift check on 11 March 2011 and taken out of service. Upon disassembly of the final drive, the outer bearing was found to be intact and undamaged, whereas the inner bearing had seized. The cage of the inner bearing was welded to its outer ring. No further units were identified as requiring detailed examination before the accident at Durham.

Identification of the immediate cause[1]

75 **The cardan shaft became detached and was not retained by its safety loops.**

76 The cardan shaft is by design supported between the gearbox and final drive by two *universal joints*, one at each end of the shaft. In order to minimise the effects of axial loads transferred by the cardan shaft, the shaft itself is made of two parts connected by a *spline* (figure 3). The spline is located towards the Voith gearbox end which means that the part of the cardan shaft attached to the Voith gearbox is short (approximately 0.4 m) and the part attached to the final drive is long (approximately 1.4 m).

77 The downward inclination of the cardan shaft when installed, combined with the presence of the spline, explains how the long part of the shaft can become released once its attachment to the final drive has fractured.

78 The release of the final drive end of the cardan shaft was due to the fracture of the input shaft within the input housing. The input shaft was found in two parts after the accident (figure 9): one part was still inside the final drive and the other was attached to the cardan shaft by the input coupling.

79 The release of the detached cardan shaft from the underside of the last vehicle was captured on the station CCTV. The station staff confirmed that the cardan shaft was found in the four-foot of the up main line in line with the end canopy of platform 2.

80 The examination of the unit carried out by the RAIB on 11 April 2011 showed that the safety loops had deformed and had been in contact with the cardan shaft. With the deformation of the safety loops, there was sufficient clearance to allow the cardan shaft to fall through (inset at figure 7).

Figure 7: UT1140 as found on 11 April 2011

[1] The condition, event or behaviour that directly resulted in the occurrence.

Identification of causal factors[2]

The detachment of the cardan shaft was due to the seizure of the outer bearing

81 **The seizure of the outer bearing led to the fracture of the input shaft which ultimately led to the detachment of the cardan shaft. The seizure of the outer bearing was a causal factor.**

82 The RAIB commissioned a metallurgical examination of the failed components in the input housing assembly. This examination located the fracture face of the input shaft marginally inboard of the outer bearing and showed evidence of heat input to the shaft with temperatures increasing towards the fracture face. The examination revealed that the input shaft had reached temperatures in excess of 850°C in the vicinity of the fracture. The shaft diameter also decreased steadily towards the fracture face (figure 8).

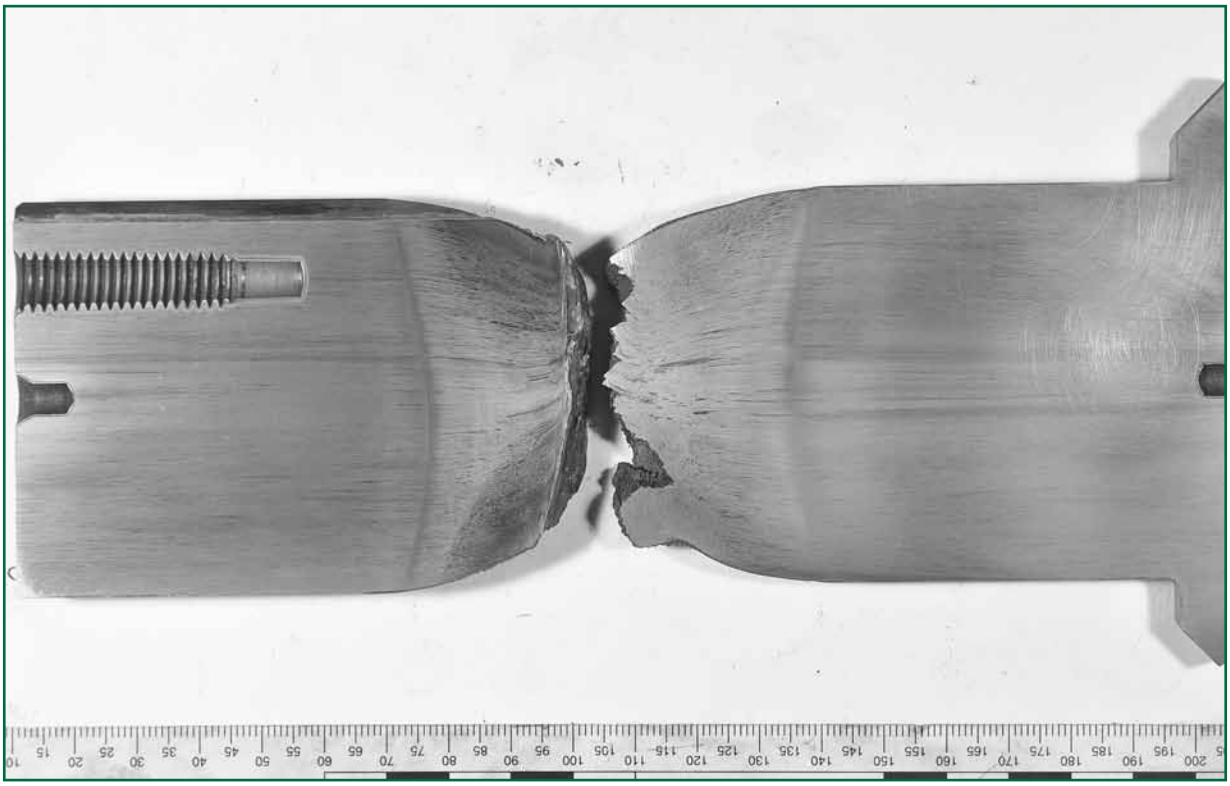


Figure 8: Section through the input shaft

83 The outer bearing was found seized and unable to rotate freely. Whereas the inner ring of the bearings is normally expected to rotate with the input shaft, the inner ring of the outer bearing on UT1140 after the accident was unable to rotate. The examination found that the inner ring had experienced temperatures in excess of 850°C. The outer bearing rollers had embedded themselves into the inner ring and some of these rollers showed flat surfaces matching the profile of the outer ring suggesting that the rollers were sliding against the outer ring at some stage during the seizure. The outer ring had bearing material smeared over the *raceway* and showed signs of having reached temperatures in the region of 500°C to 600°C.

[2] Any condition, event or behaviour that was necessary for the occurrence. Avoiding or eliminating any one of these factors would have prevented it happening.

84 The inner bearing showed no signs of significant damage or distortion and was still able to rotate freely. However, the inner bearing did show signs of exposure to heat.

85 The input coupling (figure 9) showed significant damage to the surface that had been in contact with the inner ring of the outer bearing. The examination also revealed that this area had been exposed to temperatures in excess of 820°C.

86 Analysis of the physical evidence suggests that the input shaft fractured under normal operating loads when at very high temperatures. At 850°C, the material characteristics change significantly and in particular the material strength reduces to less than one tenth of its original value at normal ambient temperature. With such a reduction in material strength, the input shaft was unable to carry the normal operating loads and fractured under a combination of torsional and tensile loads.

87 The physical evidence also indicates that the source of heat was the interface between the input shaft and the inner ring of the outer bearing after the seizure of the outer bearing. The seizure of the outer bearing was a causal factor.

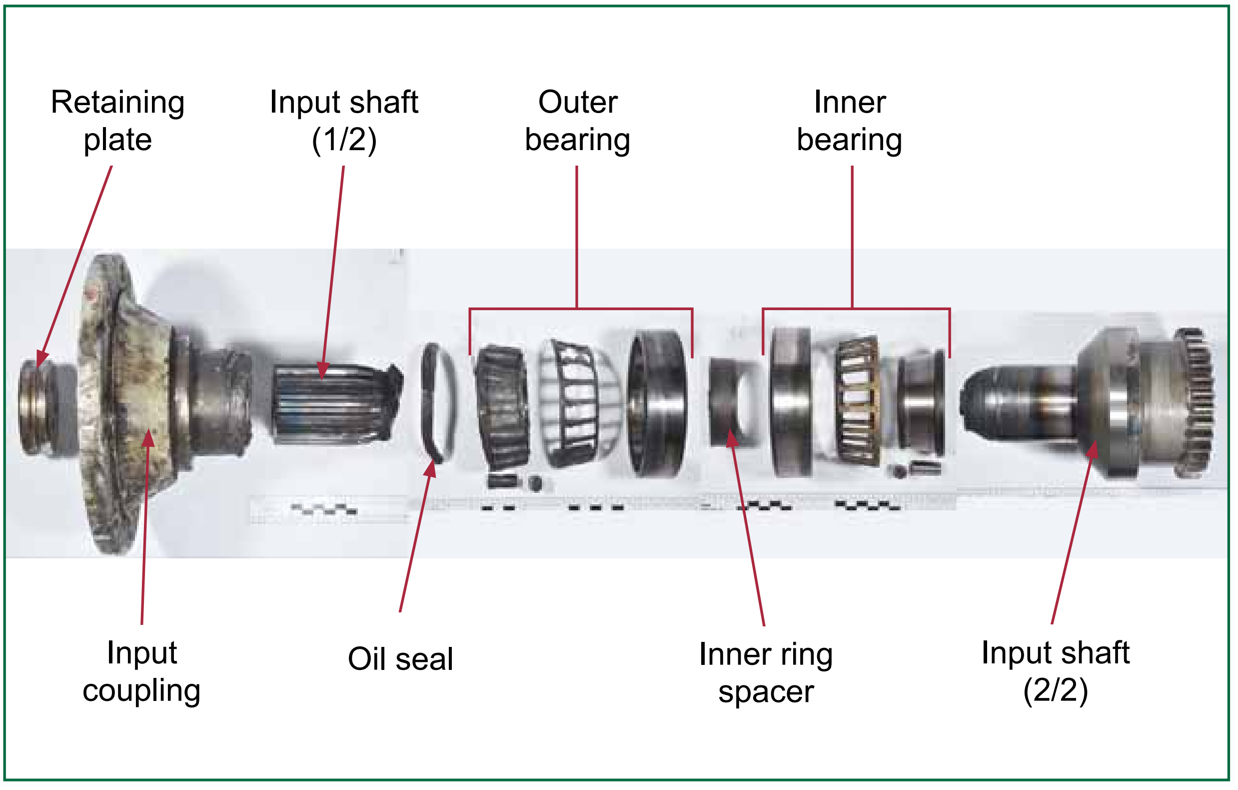


Figure 9: Components of the drive shaft input assembly following failure of the shaft

The outer bearing seizure

88 The seizure of the outer bearing was due to the combination of the following factors:

- the specified end float was small considering the high temperature difference between the inner and outer rings of the bearings;
- the actual installed end float was less than that measured at installation; and
- the uncontrolled level of misalignment led to additional loads on the bearings increasing their running temperature and further reducing the operating end float.

In addition, a number of possible factors have been identified which include:

- the introduction of the modified fit between the outer rings and the input housing, as mandated by directive GS090, may have further reduced the operating end float on the bearings;
- the specified end float measuring technique may have over-estimated the installed end float;
- the testing undertaken after the overhaul of the final drives in accordance with WI-27 may have been inadequate to detect problems with the end float setting; and
- the input bearings may have been starved of oil cooling thereby increasing their running temperature and reducing the operating end float.

Each of these factors is considered in turn, below.

The specified end float was small considering the high temperature difference between the inner and outer rings of the bearings

89 The requirement for the installed end float is defined in WI-27 to be between 51 μm and 102 μm. This is the same as in WOSS 240/3 and in the original product manual issued by SCG for the RF420i final drives. The build record shows that the installed end float was measured by LH at 76 μm on UT1140 after overhaul.

90 The industry working group (paragraph 72) commissioned a series of bench tests to determine the difference in temperature between the inner ring and the outer ring for both bearings. The setup for the tests used an input housing complete with input and pinion shafts mounted on a dummy base-plate with the shafts driven by a hydraulic pump. Oil was fed to the housing in the same way as it would be in a normal installation. The temperatures of the oil and of the housing were controlled independently by cooling blankets. Temperatures on the bearings were measured with thermo-couples embedded in the inner and outer rings of the bearings.

91 The bench tests demonstrated that the temperature difference between the inner and outer rings is greater on the outer bearing than on the inner one. The tests also showed that for a final drive set up with a positive end float and without misalignment, the typical averaged *steady-state* temperature difference from the inner ring to the outer ring is around 15°C (ie the inner ring in normal condition runs 15°C hotter than the outer ring). The tests also revealed that the *transient* temperature difference can be significantly greater than this.

92 The effect of a 15°C temperature difference is a reduction in end float of approximately 75 μm. This indicates that the bearings of UT1140 would have been running with close to zero clearance due to this factor alone.

The actual installed end float was less than that measured at installation

93 WI-27 incorrectly specifies that the end float setting is to be checked at a stage in the rebuild process when the Durlock bolts have not yet been torque tightened. Calculations and physical tests by the RAIB and the industry working group showed that the tightening of the Durlock bolts reduces the end float by 30 μm to 50 μm. This is because the Durlock bolts elastically compress the inner ring of the bearings when the torque is applied. By torque tightening the Durlock bolts after measuring the end float, the actual installed end float will be less than that measured.

94 Combined with the temperature difference across the rings, the measurement of the end float before the Durlock bolts were torque tightened means that the bearings of UT1140 would have been running with 30 μm to 50 μm of preload when in operation.

The uncontrolled level of misalignment led to additional loads on the bearings increasing their running temperature and further reducing the operating end float

95 During the controlled disassembly of UT1140, the *concentricity* of the axis of the spigot hole locating the input housing in relation to the axis of the housing bore for the bearings was measured and found to be approximately 0.5 mm. The original SCG drawing for the input housing shows that this dimension should have been controlled to be no greater than 0.05 mm (figure 10). The concentricity of the two axes was not controlled during the manufacturing of new input housings or when housing bores were re-sleeved due to excessive wear. The larger than expected concentricity resulted in the input shaft and pinion shaft being misaligned. This is confirmed by the inclined wear pattern found on the selector fork on UT1140 which is indicative of the level of permanent misalignment between the input and pinion shafts.

96 The misalignment between the shafts generated additional loads on the bearings that are used to restrain the shafts. The magnitude of these additional loads, a function of the misalignment of the shafts and of the clearances within the bearings and splines, has not been further quantified. The additional loads resulted in more heat being created within the bearings which in turn increased the temperature difference between the rings.

97 The increase in steady state temperature difference due to the misalignment of the shafts has not been quantified. Nevertheless, the effects would be additional to the reduction in operating end float already described, and the bearings of UT1140 would have been expected to run with more than 30 μm to 50 μm of preload when in operation.

The introduction of GS090 in January 2009 may have further reduced the operating end float on the bearings

98 In January 2009 and following production problems found during the assembly of the input housing, LH introduced Engineering Directive GS090 which changed the fit between the outer ring of the bearings and the input housing. The fit which was previously a *transitional fit* was changed to be an *interference fit*. A *retaining compound* was still specified to be present at the interface.

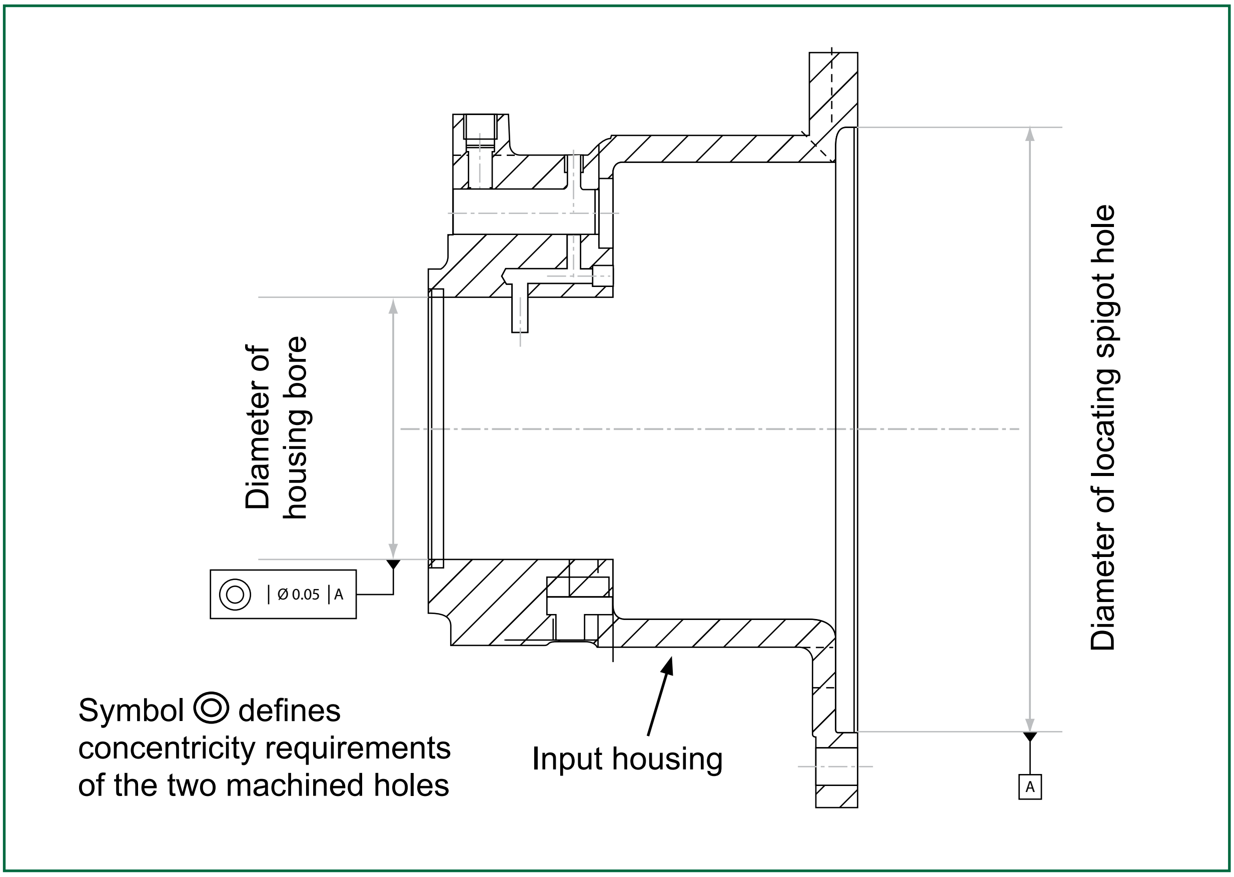


Figure 10: Concentricity of locating spigot hole relative to the housing bore for the bearings

99 The introduction of an interference between the housing and the outer ring may have had a dual effect: it may have prevented the outer ring from expanding when it warmed up, and it may have allowed for a better heat transfer from the outer ring to the housing. As the outer ring warmed up with the rest of the bearing, the tighter constraint provided by the stiff housing may have prevented the expansion of the outer ring that was previously possible. This would have reduced the operating end float. As the housing also acts as a large heat sink, the better heat transfer offered by the interference between the housing and the outer ring would have favoured a larger temperature difference between the inner and outer ring.

100 The RAIB has undertaken an assessment of the introduction of the interference using a combined thermal and structural analysis and concluded that the effects are present but likely to be small. The introduction of GS090 in January 2009 was therefore a possible factor which made the failure more likely.

The end float measuring technique may have over-estimated the installed end float

101 The end float measuring technique described in WI-27 involves the input housing assembly being located under a press (figure 11). The press clamps the input shaft stack and the fitter displaces the input housing using a crowbar wedged in between the support and the housing. The fitter uses a dial gauge to measure the achievable displacement. The gauge has a 0 - 0.1” (0 - 2.5 mm) scale and the fitter measures displacement within the range 0.002” - 0.004” (51 μm - 102 μm). The end float measuring technique is a sensitive operation with the output depending on the dexterity of the fitter.

102 The RAIB witnessed a series of tests done by the industry to establish whether this method was able to determine the end float accurately. These tests suggest that housing tilt might have been measured by the method instead of true end float. The potential inaccuracy of the measuring method has led the RAIB to conclude that it is possible that this technique contributed to the under provision of end float.

Figure 11: End float measuring technique

The final drive commissioning test after overhaul may have been inadequate to detect a problem with the end float setting

103 In accordance with WI-27, LH undertakes a commissioning test after the overhaul of each final drive. The test consists of four consecutive periods of running at an input speed of 1455 Revolutions Per Minute (RPM) for 45 mins each. The direction of rotation of the input shaft is reversed for each period. Over and above the driving torque, there is no additional load applied on the input coupling and the wheelset is unrestrained. There is no forced *convection* on the housing. Using temperature sensors fitted inside some of the housing bolts, LH monitors the temperature of the input and output bearings. The temperatures measured during the tests need to be less than 84°C to pass the commissioning test. LH also monitors the oil pressure and vibration levels for each bearing.

104 The maximum input speed for the final drive when a unit with new wheels is travelling at 75 mph (120 km/h) is 1850 RPM. The power generated within the bearings is directly proportional to the input speed. Increasing the testing speed from 1455 RPM to 1850 RPM represents an increase in power generated within the bearings of more than 25%. This increase in power equates to an increase in running temperature which would have increased the temperature difference across the rings and in turn further reduced the operating end float. Additional loads representative of the loading on the final drive together with a level of convection representative of the normal operating environment for the final drive would have compounded the effects on the temperature difference.

105 Testing in conditions more representative of the operational duty may have been sufficient to identify assemblies which were not thermally stable because of excessive preload on the bearings. Testing as specified in WI-27 therefore may have been inadequate to detect a problem with the end float setting.

The input bearings may have been starved of oil cooling thereby increasing their running temperature and reducing the operating end float

106 Unit 142045 covered the journey between Durham and Heaton depot under its own power. On arrival, the unit was quarantined by the depot staff in order to preserve the evidence. On 11 April 2011, the RAIB examined final drive UT1140 while it was still fitted to vehicle 55636 of unit 142045. There was no sign on the underside of the unit of oil leakage taking place during the trip between Durham and Heaton depot.

107 For access reasons, the unit was moved around the depot on the night between 11 and 12 April 2011. On 12 April 2011, the RAIB examined final drive UT1140 again. From the trail of oil left on the floor during the move, it became apparent that oil was leaking from the final drive at the input shaft end in noticeable quantities. On examination on 12 April 2011, the final drive was discovered to be nearly full of oil. There is no evidence that the oil was topped up at the depot in between the accident taking place and the RAIB examination.

108 The RAIB tried to determine the reasons why oil did not escape from the final drive during the trip between Durham and Heaton. One possible explanation is that oil was not being delivered to the input bearings during and immediately after the accident. During the controlled disassembly of the Durham final drive, an obstruction was found in the oil pathway leading to the bearings. Metallurgical analysis of the obstruction revealed that it was likely to have been the remnant of a metal spraying operation and would therefore have been present in the oil pathway at the time of the accident. The obstruction was large enough to partially or even fully block the delivery of oil depending on its orientation within the pathway. However, oil was witnessed to be delivered to the bearings on 12 April 2011 within the depot and on 18 April 2011 during the controlled disassembly which implies that the obstruction was not fully blocking the oil pathway at that time.

109 Analysis carried out on samples of the oil in the final drive indicated that it had been exposed to high temperatures, which suggests that some oil may have been delivered to the input bearings at the time of the accident. However, the temperatures in the input housing where the oil should have been delivered were significantly in excess of the flash temperature for the oil (200°C). At high temperatures, the oil would have been expected to vaporise and escape from the final drive through the breather. As a result the amount of oil left in the final drive after the accident should have been significantly less than was found during the examinations.

110 Evidence from other final drive failures (paragraphs 150 and 151) since the accident at Durham has suggested that oil starvation due to a blocked oil pathway or *de-priming* of the oil pump may or may not lead to input bearings seizure. The likelihood of seizure occurring is likely to be heavily dependent on the amount of end float on these bearings.

111 In light of the conflicting nature of the evidence on oil delivery and in the knowledge that oil starvation, when combined with other factors, can lead to input bearing seizure, the RAIB has concluded that it could not rule out the lack of oil delivery to the input bearings as a possible causal factor in this accident. The lack of oil delivery could be due to several factors (eg blockage, pump performance or others).

The seizure sequence

112 On the basis of the evidence from the metallurgical examination, the RAIB has postulated the likely seizure sequence. The excessive preload on the bearings combined with the long periods of running at maximum speed during the *empty coaching stock* (ECS) move led to the running temperature of the bearings rising steadily above their normal steady-state level. As the running temperature increased, the temperature difference across the bearing rose, which in turn increased the preload in the bearings. A chain reaction was created.

113 At a bearing temperature of around 150ºC, the oil was unable to maintain a lubricating film between the contact surfaces and the rate of heat generation within the bearing increased rapidly. At around 300ºC, the rollers started to soften and deformed under load. As they deformed, they lost the ability to roll on the raceways and started sliding. The physical evidence suggests that the interface with the lowest frictional resistance was the roller to outer ring interface and this is where the sliding occurred. The rollers were now stationary relative to the inner ring and were sliding against the outer ring generating a large amount of heat at this interface.

114 The heat generated within the bearings conducted into the input shaft and input coupling which were in contact with the inner ring. The part of the input shaft under the bearings and connected to the input coupling is not by design in contact with the oil, and therefore had no means to dissipate the heat that was being transferred to it. As a result, its temperature would have closely followed the bearing temperature. The input coupling has by design a smaller contact area with the inner ring than the input shaft, and hence received less heat than the input shaft. The input coupling is also normally subjected to convection with the oil and convection with fresh air. As a result, the rate of temperature increase of the input coupling would not have been as large as the rate of temperature increase of the input shaft. This difference of rate of increase in temperature resulted in the input shaft elongating more than the input coupling. As it did so, it reduced the clamping load from the Durlock bolts on the inner rings that was applied through the input coupling. The RAIB has calculated that at a bearing temperature of 300ºC, the clamping load would have all but disappeared and the inner ring would now be free to stop rotating with the input shaft. Whether it did or not would have depended on where the lowest frictional interface was within the system.

115 The large amount of heat and internal pressure at the interface between the rollers, the cage and outer ring resulted in material smearing from one surface to the other. This significantly increased the frictional resistance of this interface. As a result, sliding transferred to the interface within the system with the next lowest frictional resistance, which would have been the interfaces between the inner ring and the input shaft and coupling. The bearing would now have been completely seized with the inner ring, rollers and outer ring all stationary within the housing, while the input shaft and input coupling were still rotating at full speed.

116 The rate of heat generation at the interfaces between the inner ring and the input shaft and coupling would have increased further and the temperature of the inner ring, input shaft and input coupling rose locally to more than 850ºC. At this temperature, the input shaft material strength would have reduced to a tenth of its original value. The input shaft became unable to carry the input torque as the stresses within the input shaft exceeded its material strength. The input shaft fractured in a combination of tension and torsion. The input coupling end of the input shaft detached from the final drive.

The safety loops did not retain the cardan shaft

117 **The safety loops did not retain the detached cardan shaft. This was a causal factor.**

The design of the safety loops was unable to retain a rotating cardan shaft

118 An effective retention system for a cardan shaft would need to contain the energy stored in a large mass rotating at high speed. The two safety loops fitted to unit 142045 were to the original design for class 142/0 dating back to the mid-1980s. There was no specific load case in any of the standards applicable in the mid-1980s to cover the design of the cardan shaft safety loops. This situation remained the same in 2011. In order to accommodate the cardan shaft movement and its inclination, the loops are at different heights (figure 3). The loops are made of 10 mm steel plate, 50 mm wide welded to the underside of the vehicle body.

119 Since 2001, six incidents have been recorded where the cardan shaft became detached from the final drive. Five out of these six incidents resulted in the cardan shaft dropping on the track. There was only one incident (on 15 January 2011) in which the safety loops were successful at retaining the cardan shaft. This evidence suggests that the safety loops are unable to retain the cardan shaft presumably because of the large amount of energy stored in the shaft when it is rotating causing them to deform. The limited strength of the safety loops was a factor.

The geometry of the design was such that the detached cardan shaft could exit the cradle formed by the safety loops without requiring any deformation

120 Examination of the safety loops on 11 April 2011 found that they had deformed during the accident (inset at figure 7).

121 A further examination of several undamaged class 142 vehicles showed that a detached cardan shaft could still exit the cradle formed by the safety loops without requiring any deformation. There is enough space available to slide a detached cardan shaft in between the safety loops and the final drive. The arrangement of the safety loops was a possible factor.

122 The RAIB considered making a recommendation for the improvement of the design of the safety loops on class 142. However, the RAIB's recommendations in other areas combined with the practical difficulties associated with designing effective safety loops and the limited safety benefits obtained from an improved design led the RAIB to conclude that it would be unlikely to be reasonably practicable.

The lift checks did not detect the impending final drive failure

123 **The lift checks in place on 10 April 2011 did not detect the impending final drive failure. This was a causal factor.**

124 Up to the introduction of the lift checks on 19 February 2011 (paragraph 73), there was no means of detecting impending final drive failures. The lift checks were the first attempt to detect final drive assembly defects before they led to a detached cardan shaft. The checks detected two suspect final drives which were later confirmed to have seized bearings (paragraphs 73 and 74). There were no other in-service failures of final drives from the introduction of the lift checks to the accident at Durham.

125 The lift checks were carried out on units that had covered less than 12,000 miles since their last wheelset replacement. The checks were carried out at least every three days and were intended to identify a lift of 1 mm or more at the input coupling. The check was done by eye and feel using a crowbar wedged in between the safety loops and the underside of the input coupling. Detection of an excessive lift was therefore subject to the skill and judgement of a fitter.

126 UT1140 had covered approximately 11,700 miles at the time of the accident and hence was still included in the checks. Two days before the accident, a lift check was carried out by a fitter on UT1140 at Newton Heath depot and no lift was recorded. The lift checks as in force at the time of the accident at Durham did not detect the impending failure of final drive UT1140; this was a factor.

Identification of underlying factors[3]

127 There are two underlying factors:

- the lack of transfer of design information to LH when it took over the overhaul contract; and
- the lack of assessment of the changes to the design.

Transfer of design information

128 **The lack of transfer of information was an underlying factor.**

The original SCG product manual for the overhaul of RF420i final drives was not available to the TESCO when developing WI-27

129 The WOSS 240/3 instruction was the only document available to the TESCO in 1999 when it prepared the instruction WI-27 for overhauling the class 14x final drives. The original product manual from SCG was not available. The WOSS 240/3 instruction applied to RF42i final drives which have a different input shaft arrangement. The RF42i final drives are not sensitive to the stage of assembly at which the Durlock bolts are tightened. The TESCO adapted the overhaul process described in WOSS 240/3 to the RF420i final drive design. During this adaptation process, they introduced the concept of checking the end float before torque tightening the Durlock bolts. Had they had access to the original SCG product manual for the RF420i final drives, it is likely that they would have used the same assembly sequence as described in that document which clearly states that the retaining plate, locking plate and bolts are to be fitted and tightened before checking the end float on the assembly.

[3] Any factors associated with the overall management systems, organisational arrangements or the regulatory structure.

LH had no original final drive design documentation

130 Faced with the need to produce replacement parts for the RF420i final drives without any of the original design drawings, LH measured components in order to create drawings for all the individual parts making a final drive (paragraph 66). This exercise provided LH with a useful but incomplete set of design information. In particular, it did not provide them with any tolerancing information. As a result, LH was unable to understand that, for example, the concentricity between the housing locating spigot hole and housing bore for the bearings was an important dimension to control to ensure good alignment between the input and pinion shafts.

Assessment of design changes

131 **The lack of assessment of design changes was an underlying factor.**

LH introduced design changes to the setup of the final drive without assessing the effects of the changes

132 In January 2009, LH introduced Engineering Directive GS090 which modified the fit between the housing and the bearing outer rings. LH did not carry out any supporting analysis to assess the effects of the change and it did not make any adjustment to the end float requirement. The absence of assessment of the effects of the design change is an underlying factor to this accident.

Discounted factors

Cold start conditions

133 The bench tests carried out by the industry demonstrated that the difference of temperature across the bearing rings is exacerbated by cold conditions. With an external housing temperature as low as -17°C, the steady-state difference of temperature across the rings could reach up to 20°C which would equate to a reduction in end float of 100 μm. The tests also showed that transient temperature difference as great as 30-35°C could be experienced which would further reduce the end float.

134 The weather records from the automated weather station at Leeds and Bradford airport show that the external temperature at the time unit 142045 started its trip from Leeds was around 10°C and rising. The external temperature at the time of the accident at Durham was 19°C (paragraph 36). On the basis of this evidence, the RAIB has discounted the cold start conditions on the day of the accident as a factor in this investigation. However, the RAIB has not been able to discount that the damage to the bearings might have been initiated on a colder day before the accident and was not detected by the lift checks (paragraph 126).

Personnel issues

135 The industry working group carried out an assessment of the eight final drives that had failed in the last series of incidents (paragraph 71), including the accident at Durham, to determine whether there was a pattern in the personnel that assembled them. Three separate LH personnel had assembled the final drives, which led the working group to conclude that there was no correlation between personnel and final drive failures. The industry working group also commissioned a review of the assembly process of a complete final drive by an independent final drive specialist, who did not highlight any area of concern with regards to personnel training. On the basis of this information, the RAIB concluded that there is no evidence that personnel issues were a factor in this accident.

The introduction of CR/CI0590

136 Instruction CR/CI0590 was created in February 2004 but it was not until February 2010 that LH started using it as a reference document on the shop floor for the overhaul of the class 14x final drives (paragraph 68). CR/CI0590 has never been updated and is still in version 1A. The instruction is broadly equivalent to WI-27 in all key areas except the commissioning test where it specifies a higher testing speed than instruction WI-27. In practical terms, LH has continued to use the requirements of WI-27 to overhaul the class 14x final drives.

137 The RAIB has discounted the introduction of CR/CI0590 as a factor in this accident.

Other failure modes

138 The metallurgical examination (paragraph 82) has enabled the RAIB to discard a number of other factors on the basis of lack of evidence. These cover:

- the input shaft made out of the wrong material;
- the input shaft fracturing due to fatigue loading;
- the input shaft fracturing due to mechanical overload;
- the input shaft being subjected to excessive wear; and
- the input shaft overheating by radiation, convection or due to arcing.

Change in operational duty

139 The RAIB has compared Northern Rail's *diagrams* for class 142 in 2006 and in 2011 with a view to determining whether a change in operational duty could be linked to the failures of the final drives on class 142. The RAIB has concluded that there was no link because:

a. Northern Rail's class 142 network coverage remains broadly centred on the same geographical area (Liverpool / Manchester / Sheffield / Newcastle / Carlisle) without any new long distance destinations;

b. the average number of miles covered per day by a class 142 operated by Northern Rail remains similar; and

c. the maximum running time without stop for Northern Rail's class 142 fleet has not increased either in passenger service or in ECS mode.

Cardan shaft movement

140 Testing organised by the industry working group has highlighted that the cardan shaft experiences significant vertical movement at its lower universal joint (paragraph 146). However, on the basis that there have been no changes to the cardan shaft design or to the rubber bushes that control the movement of the final drive since first build, and that the RAIB has no evidence of earlier related failures, the RAIB considers it unlikely that the cardan shaft movement contributed to the accident at Durham.

Observations[4]

The driving of the train post-accident

141 The driver was aware that the ECML had been blocked by the accident and was keen to recover his train to Newcastle without delay. Additionally he was concerned that if he had to stop en route it could take a long time to rebuild air pressure. He therefore asked for a clear run to Newcastle and travelled at a full speed of 75 mph (120 km/h) without a full understanding of the train defects and therefore the effect of running in a degraded state.

142 At no point during the various conversations the driver had with the signaller and the maintenance controller was there any mention of a speed limit due to the degraded state of the train. The focus seemed to be more on identifying the reasons why air was leaking out of the air system and, once that leak was fixed, to move out of the way as soon as possible. The RAIB observes that there was a lack of control measures in place during the recovery phase after the accident.

The introduction of the single input shaft design

143 In 2006, following a number of selector fork failures, LH designed a modification to the final drive to remove the need for the selector fork (paragraph 69). Since 11 April 2011, all train operating companies and rolling stock owners using class 14x have agreed to the modification and all final drives currently overhauled by LH are modified accordingly.

144 The industry believes that the removal of the selector fork makes the alignment of the input and pinion shafts more critical. Since misalignment was identified as a causal factor in this investigation, the train operating companies and rolling stock owners need to be confident this modification will not introduce further risks.

Cardan shaft

145 The cardan shaft, supplied by GKN, is fitted with a universal joint at each end (figure 3). The difference in height at the ends of the cardan shaft when the vehicle is stationary leads to an *angle of deflection* at the ends of approximately 4°. Keeping the difference between the angles of deflection to a small value when in operation (less than 1° to 1.5° for high speed applications and less than 3° to 5° for low speed applications according to GKN's catalogue) is one of the essential requirements for a uniform output speed key to limiting vibrations transmitted to the final drive.

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

146 The industry working group organised a test to better understand the cardan shaft deflection angles when in operation. A camera was fitted to the underside of a class 142 to film the lower universal joint. The unit was moved around Newton Heath depot at low speeds (but high final drive input torque) and the change in deflection angle of the lower universal joint observed. This test showed that the deflection angle increases significantly when a high input torque is transmitted (low speed). The RAIB has calculated the effects of the maximum movement on the difference between the angles of deflection for both universal joints and observes that the difference exceeds the value quoted by GKN in its design documentation for low speed applications.

Previous occurrences of a similar character

147 Between March 2000 and April 2011, more than 60 final drive incidents were recorded on class 14x units (paragraph 70). Before the accident at Durham, a total of 17 final drive incidents that featured failed input bearings had occurred (paragraph 71).

148 On 12 May 2003, unit 158839 derailed by three axles at Aberystwyth, Wales on a set of facing points. The derailment resulted from the detachment of the cardan shaft connecting the two final drives on the same bogie (master and slave arrangement). RSSB[5] investigated this accident and reported that the detachment was due to a fatigue failure of the pinion shaft bearing on the slave final drive. The underlying factors included the possibility that the bearings had been preloaded radially when the drive was overhauled. RSSB also commented on the failure of the safety loops to retain the cardan shaft which ultimately led to the derailment. RSSB made a recommendation to improve the design of the safety loops on class 158 following the accident. This recommendation was subsequently rejected by the industry on the basis of a cost benefit analysis and was never implemented.

149 On 20 February 2010, a seven-car class 222 Meridian passenger train derailed near East Langton, Leicestershire. One axle of the fourth vehicle derailed while the train was travelling at a speed of 94 mph (151 km/h), and it subsequently ran for a distance of approximately 2 miles (3.2 km) before it stopped. There were no injuries among the 190 passengers and five crew on board the train, but there was damage to the track and the train, including spillage of diesel fuel. The investigation found that the derailment resulted from a complete fracture of a powered axle, caused by the inner ring of a tapered roller bearing inside the axle-mounted final drive, spinning on the axle. This spinning, which should normally never happen, was initiated by the bearing becoming stiff in rotation, and resulted in the consequent generation of a large amount of frictional heat which ultimately led to the axle weakening and fracturing. The destruction of some key evidence in the failure made it impossible to determine with certainty the precise sequence of events leading to the bearing becoming stiff. The RAIB's view, based on the available evidence, is that the bearing stiffening was most likely initiated by a problem with the fit between the inner ring of the bearing and the axle. Although similar in some aspects to the accident at Durham, the cause and outcome of the bearing failure at East Langton were different.

[5] The company is registered as 'Rail Safety and Standards Board', but trades as 'RSSB'.

150 On 1 August 2011, vehicle 55787 of unit 142091 was undergoing a routine overhaul at Heaton depot. The overhaul included the temporary removal of the complete final drive and wheelset from the vehicle to enable the replacement of the *axleboxes*. The wheelset was temporarily allowed to rotate downwards and when returned to the normal position, it was found that something inside the final drive was acting like a ratchet and permitted rotation in only one direction. The final drive had been overhauled by LH and fitted to vehicle 55787 by Northern Rail in May 2010. The unit had covered 125,880 miles since then. The industry investigation identified that the oil pump spindle had snapped releasing the gear driving the oil pump. As a result the oil pump was not operating and was not delivering oil to any part within the final drive. The investigation also showed severe wear marks on the oil pump base casting where the gear had dropped, suggesting that the detachment of the gear was not a recent event. The end float on the input bearings was measured and found to be more than double the maximum specified limit in WI-27. The industry investigation concluded that in this case of oil starvation, the continued operation of the input bearings was mainly due to the large end float measured on the bearings. The industry investigation also concluded that the large end float on the input bearings may have arisen as a result of the inaccurate method of measurement in use at the time of overhaul of the final drive (May 2010).

151 On 26 April 2012, at 22:52 hrs, a cardan shaft fell near Plawsworth viaduct from an empty class 142 passenger train travelling at 75 mph (120 km/h). The immediate cause of the detachment was the complete fracture of the final drive input shaft. The input shaft fractured following the seizure of the two input bearings. The final drive had been overhauled by LH in November 2010 and fitted to vehicle 55544 of unit 142003 on 15 December 2010 by Northern Rail. The unit had since covered 105,000 miles. The unit had recently been subjected to a major pre-planned and routine overhaul at Heaton depot which was completed on 24 April 2012. The routine overhaul included the temporary removal of the complete final drive and wheelset from the vehicle to enable the replacement of the axleboxes. The cardan shaft and torque reaction arm were also replaced during the overhaul. The initial industry investigation into the incident identified that the seizure of the bearings was likely to have been triggered by oil starvation following the de-priming of the oil pump combined with other factors. The reasons for the de-priming of the pump are currently unclear but could be associated with the work that was carried out two days previously during the routine overhaul (eg inadequate handling of the final drive, oil contamination or some other factors). The industry is undertaking an investigation into the circumstances of this incident.

Summary of conclusions

Immediate cause

152 The cardan shaft became detached and was not retained by the safety loops (**paragraph 75**).

Causal factors

153 The seizure of the outer bearing on the input shaft of the final drive was the causal factor in the cardan shaft becoming detached (**paragraph 81**).

154 The seizure of the outer bearing was due to the combination of the following factors:

a. the specified end float was small considering the high temperature difference across the bearing rings (**paragraph 92, Recommendation 1**);

b. the actual installed end float was less than that measured at installation (**paragraph 94, Recommendation 1**); and

c. the uncontrolled level of misalignment led to additional loads on the bearings increasing their running temperature and further reducing the operating end float (**paragraph 97, Recommendation 1**).

155 It is possible that the following were factors in the seizure of the outer bearing:

a. the introduction of GS090 in January 2009 may have further reduced the operating end float on the bearings (**paragraph 100, Recommendation 1**);

b. the specified end float measuring technique may have over-estimated the installed end float (**paragraph 102**);

c. the testing as specified in WI-27 may have been inadequate to detect the problem with the end float setting (**paragraph 105, Recommendation 5**); and

d. the input bearings may have been starved of oil cooling thereby increasing their running temperature and reducing the operating end float (**paragraph 111, Recommendation 1**).

156 The seizure of the outer bearing was not detected by the lift checks and this was a causal factor (**paragraph 123, Recommendation 3**).

157 The detached cardan shaft was not retained by the safety loops and this was a causal factor. The safety loops did not retain the cardan shaft because of the following factors:

a. the design of the safety loops was unable to retain a rotating cardan shaft (**paragraph 119**); and

b. the geometry of the design was such that the detached cardan shaft could exit the cradle formed by the safety loops without requiring any deformation (**paragraph 121**).

Underlying factors

158 The underlying factors were:

a. the original SCG product manual for the overhaul of RF420i final drives was not available to the TESCO when developing WI-27 (**paragraph 129, Recommendation 4**);

b. LH had no access to the original design drawings for the final drive (**paragraph 130, Recommendation 4**); and

c. LH introduced design changes to the setup of the final drive without assessing the effects of the changes (**paragraph 132, Recommendation 2**).

Additional observations

159 Although not linked to the accident on 10 April 2011:

a. there was a lack of control measures in place during the recovery phase of the accident (**paragraph 142, Recommendation 6**);

b. the modification to replace the selector fork might make the alignment of the input and pinion shafts more critical (**paragraph 144, Recommendations 1 and 2**); and

c. at low speeds, the cardan shaft operates with large deflection angles and the difference in deflection angles exceeds the manufacturer's recommended limit (**paragraph 146**).

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

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

160 LH has modified the overhaul sequence to ensure that the end float measurement is carried out after the Durlock bolts have been torque tightened. This modification has been implemented.

161 LH has devised a new end float measuring jig. It uses a hydraulic cylinder to displace the input shaft within the housing and it measures the end float with a refined Dial Test Indicator (DTI). This jig is now used by LH to measure end float.

162 The high speed and conventional Technical Specifications for Interoperability (TSI) mandate the preparation of a Technical File which must be kept throughout the service life of traction and rolling stock equipment. The TSIs specify a comprehensive list of maintenance information that should be part of the Technical File. This includes details of components, assembly/disassembly drawings and maintenance criteria. The Railways (Interoperability) Regulations 2011 mandates that the ownership of the Technical File rests with the equipment owner for its service life. The RAIB has not had cause to investigate whether the implementation of the high speed or conventional TSI is providing the owners, operators and overhaulers with the required technical information for the effective maintenance of components such as final drives.

Other reported actions

163 Northern Rail has implemented revised lift checks:

- with a view to detecting lift no greater than 0.35 mm using a DTI;
- to be carried out at least every two days (instead of three previously);
- on units having covered less than 18,000 miles since the last wheelset replacement (instead of 12,000 miles previously); and
- to include a check of the temperature indicators now fitted to the final drives.

Northern Rail has also limited the speed of the vehicles to 60 mph (96 km/h) for the first 18,000 miles after final drive replacement.

164 Instruction CR/CI0590 is currently under review by the industry working group (paragraph 72). Once revised, CR/CI0590 will cover the modified design of the final drive without the selector fork. This update to CR/CI0590 is on-going.

165 The industry working group has proposed changes to the specified end float requirement currently set at 51 μm to 102 μm. On the basis of analysis and testing work carried out by the industry on the modified design of the final drive without the selector fork, the working group has proposed that the end float should be set at 102 μm to 152 μm. This modification has been implemented by LH. A final end float setting requirement will need to be confirmed in the revision of CR/CI0590 upon completion of the analysis work (Recommendation 1).

166 Northern Rail has stated that it has started a programme to fit a temperature intervention system on class 14x vehicles that have recently been fitted with an overhauled wheelset and final drive. The system monitors the temperature of the final drive and intervenes if the temperature gets too high. If the measured temperature exceeds 100°C, a warning light flashes in the cab to alert the driver. If the measured temperature exceeds 120°C, the system intervenes and shuts down the relevant engine. Northern Rail is reviewing its position with regards to fitment of the temperature intervention system to the rest of the class 14x fleet (Recommendation 3).

167 Northern Rail has stated that it has reviewed the post accident actions that were taken and its contingency plans for dealing with defective on-train equipment. In the light of its review, Northern Rail has reported that it has decided to strengthen its contingency plans, and that it is reviewing the competence and knowledge of the driver, the requirements for attendance of maintenance fitters and also communications during incidents (Recommendation 6).

Recommendations

168 The following recommendations are made[6]:

1 *The objective of this recommendation is to ensure that the industry completes the work that has already started on reviewing the end float and alignment requirements, as well as the bearing fit as soon as possible and incorporates the relevant changes in a revised overhaul procedure. This recommendation also includes the need for the industry to review the performance of the oil pump particularly in light of the more recent incident at Plawsworth (paragraph 151).*

The owners of class 14x vehicles, in consultation with suppliers of overhaul services, should review the final drive design, design tolerances and the maintenance processes in respect of:

- end float setting (paragraphs 154a and 154b);
- input and pinion shafts alignment (paragraph 154c);
- fit of the bearings in the housing bore (paragraph 155a); and
- oil pump performance (paragraph 155d).

Any required changes identified by the review should be suitably documented and incorporated in overhaul procedures.

This recommendation applies to the modified design of the final drive (paragraph 159b).

2 *The objective of this recommendation is to ensure that designers of railway equipment validate any changes to the design of safety critical components.*

The owners of class 14x vehicles should review the adequacy of their existing arrangements for ensuring that the suppliers of their equipment validate changes to the design of safety critical components (paragraphs 158c and 159b).

continued

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

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

(a) ensure that recommendations are duly considered and where appropriate acted upon; and

(b) report back to RAIB details of any implementation measures, or the reasons why no implementation measures are being taken.

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

3 *The objective of this recommendation is to ensure that Northern Rail has in place risk control measures to detect impending final drive failures before they occur.*

Northern Rail, in consultation with the owners of class 14x vehicles, should develop, validate and implement measure(s) to identify and prevent the onset of failure of a recently overhauled final drive so as to prevent complete failure where practicable (paragraphs 156 and 166).

Note: the measure(s) implemented to address this recommendation may be appropriate to all class 14x final drives.

4 *The objective of this recommendation is to ensure that key design information is made available to companies undertaking work on class 14x final drives.*

For class 14x vehicles, vehicle owners in consultation with operators should review whether the necessary technical information for the maintenance and overhaul information of the class 14x final drives is still available and if it is, they should arrange for it to be sourced. This information should be kept by the vehicle owners and made available to all existing and future operators, maintainers and overhaulers as relevant (paragraphs 158a and 158b).

Note: the principle outlined in this recommendation may also apply to other traction and rolling stock equipment and other fleets of train.

5 *The objective of this recommendation is to ensure that the final drives are tested in conditions representative of their operational duty before being released to the operator.*

The owners of class 14x vehicles should review the testing of the final drives after overhaul to confirm that it is done in conditions sufficiently representative of their operational duty and where appropriate amend the testing requirements accordingly. The following areas should be considered:

- operational speed;
- loading on the shafts; and
- external environmental conditions (paragraph 155c).

6 *The objective of this recommendation is to ensure that Northern Rail's plans for dealing with accidents and incidents are adequate.*

Northern Rail should complete the review of its procedures governing post-accident actions and implement any necessary changes to ensure that the risks to personnel and the environment from movement of damaged trains and trains with defective equipment is appropriately managed (paragraphs 159a and 167).

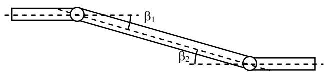
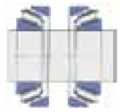
Appendices

Appendix A - Glossary of abbreviations and acronyms

AC	Alternating Current
BREL	British Rail Engineering Limited
CCF	Control Centre of the Future
CCTV	Closed Circuit Television
DTI	Dial Test Indicator
ECML	East Coast Main Line
ECS	Empty Coaching Stock
OTDR	On-Train Data Recorder
RPM	Revolutions per Minute
RSSB	Rail Safety and Standards Board
SCC	Signalling Control Centre
SCG	Self Changing Gears
TESCO	Technical Engineering Service Company
TSI	Technical Specifications for Interoperability
WOSS	Workshop Overhaul Standard Specification

Appendix B - Glossary of terms

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

Angle of deflection	For a cardan shaft, the angles at which the universal joints are operating. 
Axlebox	The axle bearing housing which connects the wheelset to a rail vehicle. There is one axlebox at each end of a wheelset.*
Back-to-back	The mounting arrangement of tapered roller bearings where the narrow part of the inner rings are facing each other. 
Ballast	Crushed stone, nominally 48 mm in size and of a prescribed angularity, used to support sleepers or bearers both vertically and laterally.*
Cardan shaft	A shaft with a universal joint at each end, which transmits torque and rotation between two misaligned components of a transmission system, in the case of this report, between a body mounted gearbox and a final drive on the axle.
Chain(s)	A unit of length, being 66 feet or 22 yards (approximately 20.117 metres). There are 80 chains in one standard mile.*
Concentricity	In the context of this report, a measure of how close the respective axes of two machined holes are.
Control Centre of the Future	Network Rail's information display system which shows current train position and punctuality information on bespoke railway network maps. It has a replay function which enables the passage of trains to be recreated.
Convection	The transfer of heat by the circulation or movement of a liquid or gas over the surface of a component at a different temperature. One of the three modes of heat transfer (others are conduction and radiation).
De-priming	In the context of this report, a condition in which the oil pump looses the ability to deliver oil to the final drive. The oil pump might also have the ability of re-priming itself (ie it might be able to regain the ability to deliver oil to the final drive).
Diagrams	The document giving details of which rail vehicles shall work which services.*
Down main	A track on which the normal direction of trains is in the down direction, ie away from London (in this case towards Newcastle).*
Down slow	The name generally given to the nominally less important of the two down lines in a three or four track railway. It may or may not be slower than the other down line.*

Durlock	A commercially available brand of fasteners which features a serrated surface under the fastener head to ensure good gripping with its mating part.
Empty Coaching Stock	The term for a train consisting of empty passenger vehicles being moved from one place to another.*
Final drive	A final drive is mounted on each powered axle and transmits the drive from the gearbox, through an angle of 90 degrees, into the axle.
Four-aspect colour light signals	A signal capable of displaying four aspects: green (proceed), double yellow (preliminary caution), yellow (caution) and red (stop).
Four-foot	The area between the rails on which trains on the national network run.*
Input bearings	The bearings located on the input side to the final drive (ie closer to the cardan shaft). The output bearings are axle-mounted.
Interference fit	In the context of this report, a fit between the housing and bearing outer ring where the outer diameter of the outer ring is slightly greater than the housing diameter. When fitted together the ring is tight within the housing and not free to rotate. The greater the difference in diameters, the greater is the level of interference and tightness.
Loop	Any short length of track connected to another line at both ends.*
Main reservoir	An air reservoir on a railway vehicle that feeds the air systems on the vehicle.
On train data recorder	Equipment fitted on board the train which records the train's speed and the status of various controls and systems relating to its operation. This data is recorded to a crash-proof memory and is used to analyse driver performance and train behaviour during normal operations or following an incident or accident. This equipment may also be known as an OTMR, Black Box or Incident Recorder.
Preloaded	In the context of this report, a condition in which the bearing runs without any internal clearance between rollers and raceways. Beyond a certain level of preload, which is specific to the type of bearing, the amount of heat generated within the bearing rises rapidly and this can lead to bearing failure.
Raceway (of a bearing)	The polished part of the bearing inner and outer rings on which the rollers run (figure 5).
Retaining compound	A substance used to fill the inner space between components which once cured forms a strong assembly.

Retention devices	A means to catch a failed component before it drops onto the track.
Ring (of a bearing)	One of the two cylindrical parts making up the body of a bearing (figure 5). The inner ring is the smaller part and the outer ring is the larger one. Usually, one is stationary and the other one rotates. Sometimes referred to as a 'race' or 'cup and cone'.
Safety loops	A form of retention devices which takes the shape of loops made from steel sections encircling a component.
Signal post telephone	A telephone located on or near a signal that allows a driver or other member of staff to communicate only with the controlling signal box.*
Single reduction bevel gearbox	A gearbox with a reduction ratio which transmits the drive from the engine through an angle of 90 degrees into the axle.
Spline	A series of gear-like teeth on a shaft that fit into slots on a corresponding shaft, enabling both to rotate together whilst allowing longitudinal movement between the two shafts.
Steady state	Describes a parameter that has reached a stable condition (ie its value is not changing over time).
Tapered roller bearings	A bearing that uses tapered rollers running on coned raceways and that is able to transfer axial load as well as radial load (figure 5).
Technical Engineering Service Company (TESCO)	A company that provides technical engineering or consultancy services to the rail industry.
Transient	Describes an event of relatively short duration.
Transitional fit	In the context of this report, a fit between the housing and bearing outer ring where the outer diameter of the outer ring is either slightly greater or slightly smaller than the housing diameter. As a result, the fit between the bearing and the housing is either an interference or a clearance.
Universal joint	A joint that transmits rotating motion between two shafts that are not necessarily in a straight line.
Up main	A track on which the normal direction of trains is in the up direction, ie towards London (in this case towards York).*
Wheelset	Two rail wheels mounted on their joining axle.*

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