# Rail Accident Report

## Passenger train derailment near East Langton, Leicestershire
## 20 February 2010

Report 01/2012
January 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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# Passenger train derailment near East Langton, Leicestershire, 20 February 2010

## Contents

# Summary


On 20 February 2010, at around 15:49 hrs, a seven-car Meridian diesel multiple unit passenger train derailed by one axle of the fourth vehicle, while travelling on the Midland Main Line near East Langton. The train was travelling at a speed of 94 mph (151 km/h) when the derailment occurred, and it subsequently ran for a distance of approximately 2 miles (3.2 km) before it stopped. The train remained upright during the derailment and did not foul the adjacent line. There were no injuries among the 190 passengers and 5 crew who were on board the train, but there was damage to the track and the train, including loss of diesel fuel.

The immediate cause of the derailment was the complete fracture of the powered trailing axle of the leading bogie on the fourth vehicle. The fracture occurred underneath the gear-side output bearing of the final drive and was caused by this bearing stiffening up so that it could no longer rotate normally. When this happened the axle spun within the inner race of the bearing to which it is normally tightly fitted. The consequent generation of a large amount of frictional heat between the axle and bearing resulted in the axle being locally heated to a high temperature and weakened to the point it could no longer carry its normal loading.

Key evidence about the condition of the bearing and its fit onto the axle was destroyed in the failure, making it impossible to determine with certainty, the precise sequence of events leading to the bearing becoming stiff in rotation. The RAIB investigation has interpreted the available evidence in order to identify the most likely cause of the failure from the possible causes. The RAIB concluded that the most likely cause of the bearing failure which preceded the overheating of the axle was a loose fit between the gear-side output bearing and axle.

The RAIB has made four recommendations. Two recommendations relate to reviewing the design and overhaul procedures for final drive gearboxes on Meridians and other rolling stock. They also cover consideration of the detection of overheating output bearings in order to mitigate risk to persons resulting from a failure of the output bearings, regardless of the cause. A third recommendation relates to the oil sampling regime used for the Meridian fleet and the fourth relates to the provision of practical, simulation based alarm handling training for drivers and train crew.

# 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 Dimensions in this report are given in metric units, except speed, distance, and locations on Network Rail, which are given in imperial units, in accordance with normal railway practice. In this case the equivalent metric value is also given. Location information is given relative to a 'zero' datum at London St Pancras, measured in miles and *chains.*

4 References to 'right' and 'left' side of the train or track are made relative to the direction of travel of the train.

5 References to 'inboard' and 'outboard' components are made relative to the vehicle's longitudinal centre line; inboard items are those nearest to the centre line.

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

# The accident

## Summary of the accident

7 At around 15:49 hrs on 20 February 2010, train 1F45, which formed the 14:55 hrs service from London to Sheffield, derailed while running at a speed of 94 mph (151 km/h) on the *down* line of the Midland Main Line near East Langton village (figure 1). One axle derailed, having broken into two parts.

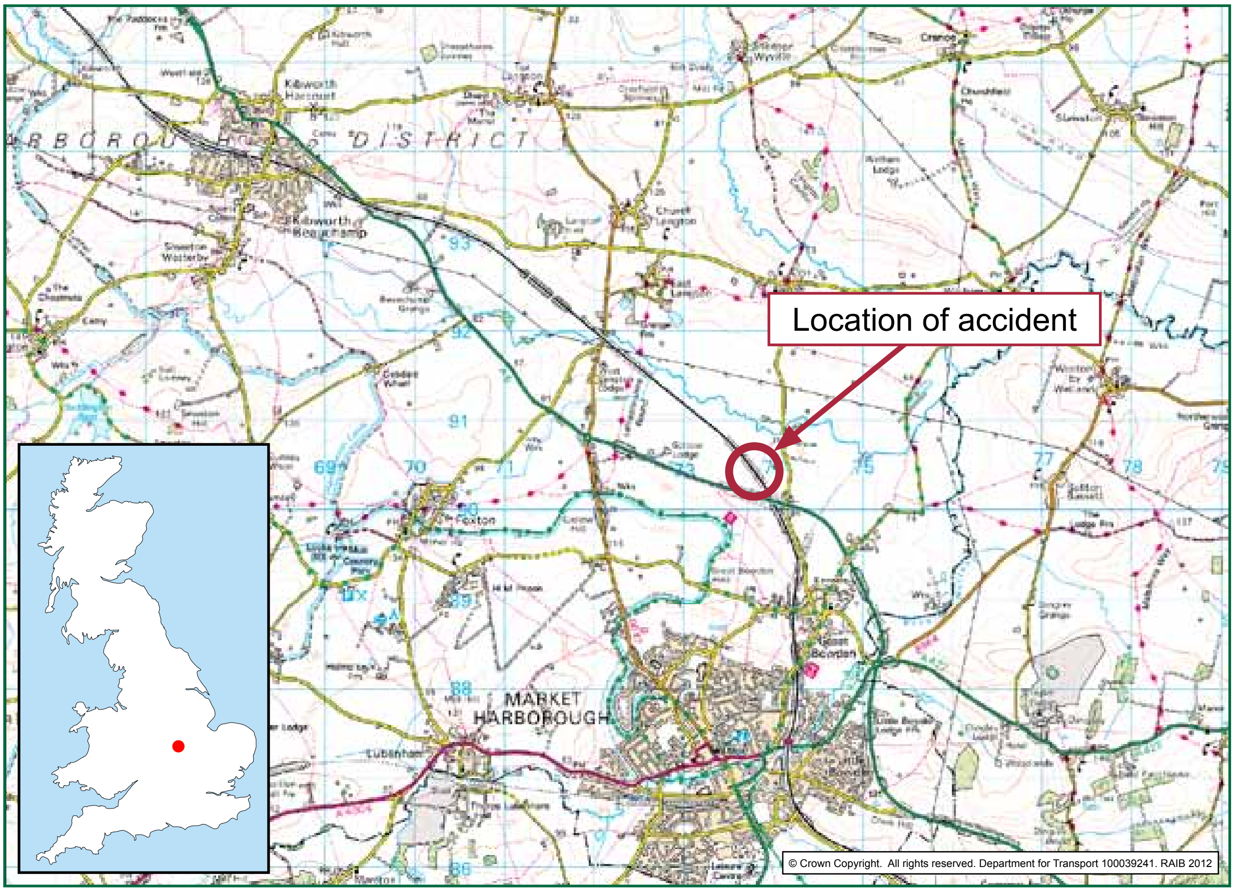


*Figure 1: Location of accident*

8 The train, a seven-car Class 222 Meridian, ran derailed for approximately 2 miles (3.2 km) before stopping. The derailed axle was the trailing axle of the leading *bogie* of the fourth vehicle. All the vehicles remained upright and clear of the adjacent *up* line throughout the derailment. Figure 2 shows the derailed left-hand side wheel.

9 There were 5 crew members and approximately 190 passengers on board the train. There were no reported injuries.


*Figure 2: Derailed trailing wheelset of leading bogie (fourth vehicle)*

10 The derailment caused a significant amount of infrastructure damage. Approximately 1100 sleepers, a lineside *hot axle box detector* (HABD) at East Langton, an *Automatic Warning System* (AWS) magnet and various cables had to be replaced. The decking of the footpath crossing at Thorpe Langton was destroyed and road vehicles passing under a railway bridge were reported to have been showered with ballast. There was damage to the underframe and bogies of the derailed vehicle and those following. A fuel tank on the fourth vehicle was punctured and around 1,000 litres of diesel fuel was estimated by RAIB to have been spilled. The down main line was closed until 02:00 hrs on 23 February 2010.

## Organisations involved

11 Train 1F45 was operated by East Midlands Trains, who also employed the driver and other on-train crew.

12 The maintenance of the train was carried out at Etches Park Depot in Derby by Bombardier Transportation (Bombardier), who was also the manufacturer of the train.

13 The train was owned by HSBC Rail (UK) Limited at the time of the accident and is now owned by European Rail Finance Holdings Limited which is a member of the Eversholt Rail Group. HSBC Rail (UK) appointed Atkins Rail as the *Notified Body*.

14 The axles and wheels of the Meridian were designed by Bombardier and manufactured to its specification by Lucchini Group in Italy.

15 The *final drive gearbox* was designed and manufactured by Voith Turbo in Germany to a *functional specification* from Bombardier.

16 The output bearings of the final drive gearbox (explained in paragraph 64) were supplied to Voith by the Timken Company (Timken) and were manufactured in the USA.

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

18 All the above organisations freely co-operated with the RAIB and provided assistance during the course of this investigation. Some of these organisations also participated in a technical group set up to plan and direct the forensic examinations and testing work that was undertaken (paragraph 60).

## Location

19 The derailment occurred on a rural section of the down main line between Market Harborough and Leicester, near East Langton, starting on the left-hand curve north of Market Harborough station and finishing on the subsequent straight section (figure 3).

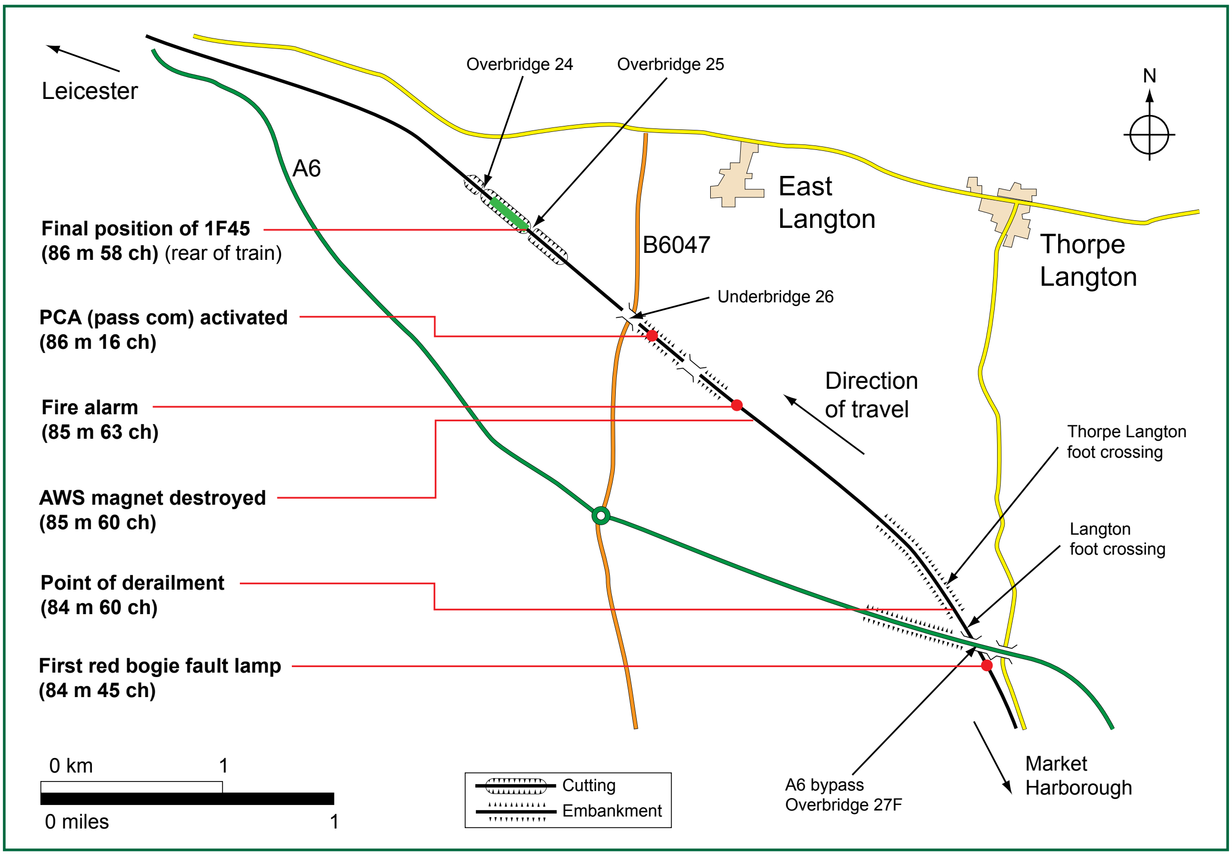


*Figure 3: Location of the derailment*

20 The first signs of the axle breaking were irregular marks on the rail heads of the down line, approximately one wheel revolution apart, starting at 84 miles 30 chains. The left wheel derailed to the *cess* side at 84 miles 60 chains and the right wheel derailed into the *four-foot* at 84 miles 65 chains. The train came to rest in a cutting at 86 miles 58 chains.

21 The railway at this location is double track with a permitted speed of 100 mph (161 km/h). The first part of this section of railway lies on an embankment (figure 4) which merges progressively into a cutting at the end of this section. The gradient of the line after Market Harborough station falls gently at between 1 in 165 and 1 in 500 to around the 86 mile post and then rises at 1 in 167 towards overbridge 25. The track construction in this area is continuous welded rail (CWR), laid on concrete sleepers. The condition of the track did not contribute to the accident.


*Figure 4: The derailment site and the destroyed Thorpe Langton foot crossing*

## External circumstances

22 The weather on the day of the accident was fine and dry with clear visibility. The temperature in the East Langton area ranged from a minimum of around -3°C to a maximum of around +3°C. There had been a period of cold weather along the whole route in the days before the accident.

## The train

23 The train was unit 222005, a seven-car Class 222 Meridian *diesel electric multiple unit* (DEMU), designed and built by Bombardier (an example is shown in figure 5). The Meridian, which is a derivative of, and broadly similar to, the Class 220 Voyager trains also built by Bombardier, was designed for a maximum speed of 125 mph (201 km/h) and entered service on the Midland Main Line in May 2004.


*Figure 5: Example of a Meridian Class 222 unit (courtesy of East Midlands Trains)*

24 Each vehicle has two bogies, each with two *wheelsets*, an inner powered wheelset (nearer the middle of the vehicle) and an outer unpowered wheelset (nearer the vehicle end). Both types of wheelsets have *hollow axles and inboard axle bearings* (figure 6). The wheelset which fractured at East Langton was a powered wheelset and had been in service for 922,000 miles (1.48 million km).

25 A single diesel engine on each vehicle powers two body mounted *traction motors*. Each motor drives a powered wheelset through a *cardan shaft* and an axle mounted final drive gearbox (figure 6).

26 Her Majesty's Railway Inspectorate (HMRI) authorised the Class 222 trains to enter service under the Railways (Interoperability) (High-Speed) Regulations 2002 (HIS), following an assessment by the Notified Body and submission of a technical file documenting conformity with relevant standards.

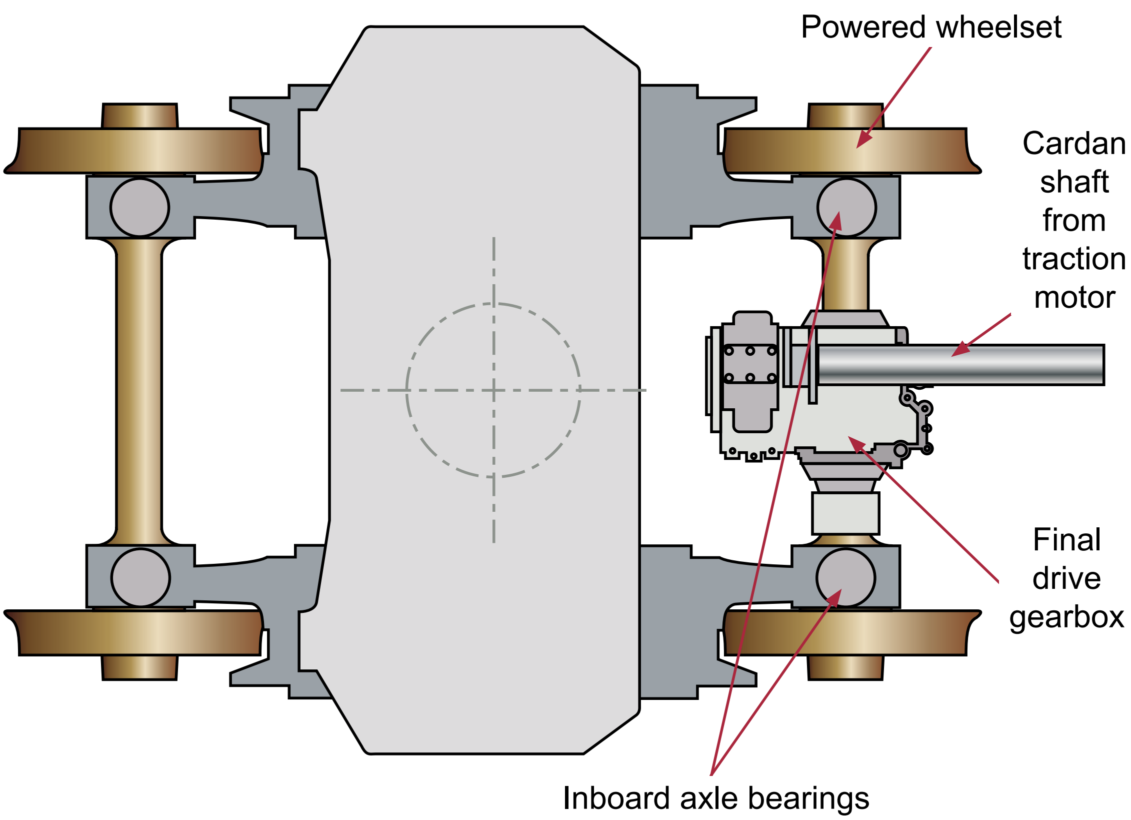


*Figure 6: Schematic plan view of bogie, final drive gearbox, cardan shaft and inboard axle bearings*

## Staff involved

27 The member of the maintenance team, who changed the gearbox oil during the last maintenance work prior to the accident, was a contractor employed by Bombardier and had worked at Etches Park Depot for three months. He had been trained and assessed by Bombardier for the tasks he was required to do and had carried out oil changes on these gearboxes many times before without incident.

28 The maintenance technician who carried out an independent check that the oil change had been correctly carried out (as required by the procedures for oil change) was employed directly by Bombardier. He had worked for four years at Etches Park Depot, exclusively on the Meridian fleet and was familiar with this task.

29 The driver of train 1F45 had qualified as a train driver in December 2004 with another train operating company and had been employed by East Midlands Trains since September 2008, qualifying on the Class 222 Meridian in October 2008. His last formal competence assessment, which he passed successfully, was in October 2009. He had two previous minor incidents on his record, which do not directly relate to this accident.

## Events preceding the accident

30 On 14 February 2010, unit 222005 entered Etches Park Depot to commence its routine B examination (36 day interval) and remained there until 19 February 2010 when it returned to normal passenger service. The tasks performed during this period that were relevant to the wheelsets and final drive gearboxes, were oil sampling, oil change, and oil level and leakage checks. The oil change is routinely carried out every third B exam (108 day interval) and the other tasks are done at every B exam. Standard practice at that time was to carry out maintenance on the first four vehicles and then reverse the train to complete the tasks on the remaining three vehicles (because the depot shed was too short to fully accommodate a seven-car Meridian unit). The reversal of the train took place on 17 February 2010. This is discussed further at paragraph D29 of appendix D.

31 During the B exam, oil samples were taken from each of the 14 final drive gearboxes on unit 222005, the oil was drained and each gearbox refilled. The oil levels were then independently checked by a maintenance technician. The two staff who attended the final drives both stated that they did not notice anything unusual such as signs of overheating, excessive oil leakage or loose bolts on the gearboxes. The oil samples taken during this exam, and subsequently analysed using Bombardier's standard procedures, showed nothing abnormal on the accident wheelset (serial number E1692/07) on vehicle 60625 or on any other final drives on the unit.

32 On the morning of 19 February 2010, the unit was prepared for service at the depot and then formed the 07:20 hrs train from Derby to Sheffield. During the course of that day, unit 222005 made two full round trips between Sheffield and London. It then ran again between Sheffield and London before returning to Derby Etches Park, arriving at 23:39 hrs, having covered a total of 993 miles (1598 km).

33 On 20 February 2010, unit 222005 commenced service as 1F00, the 06:26 hrs train from Derby to Sheffield. It ran one full round trip between Sheffield and London and returned to London, having run a further 537 miles (864 km). In that time, set 222005 made three passes over a *wheel impact load detector* at Thurmaston, approximately 2 miles (3.2 km) north of Leicester (at 08:20 hrs, 11:08 hrs, and 13:20 hrs). It did not set off any alarms and the traces from these passes show nothing abnormal about the running of wheelset E1692/07.

34 Meanwhile, the driver of train 1F45 booked on for duty at Derby depot and commenced his shift at 09:48 hrs. He drove a train to London St Pancras and, following a break, he joined unit 222005 to drive train 1F45, which was due to depart from St Pancras at 14:55 hrs for Sheffield, via Leicester and Derby. He carried out routine pre-service checks and the train departed on time, and then ran non-stop until it derailed near East Langton, a distance of 86.7 miles (140 km).

## Events during the accident

The train and the driver's actions

35 The journey from London to Market Harborough was uneventful with no faults (or 'anomalies') being logged by the *Train Management System* (TMS). Train 1F45 passed Market Harborough Station (82 miles 74 chains from London St Pancras) at 15:47 hrs, three minutes early, at a speed of 58 mph (93 km/h) to comply with the local speed limit there. The driver then initially accelerated to a speed of 85 mph (137 km/h) and on reaching the next speed board on Great Langton curve (84 miles 24 chains), he accelerated further, intending to bring the train up to the line speed of 100 mph (161 km/h).

36 At 84 miles 30 chains, the second (powered) wheelset of the fourth vehicle (60625) began to behave abnormally, leaving irregular marks on the rail head (paragraph 20). As the train traversed Great Langton curve, the driver recalled feeling a slight jolt, which he did not consider abnormal, and continued to accelerate.

37 At 15:48:50 hrs, when the train was at around 84 miles 45 chains, and its speed as recorded by the *On Train Data Recorder* (OTDR) was 94 mph (151 km/h), the driver received a red bogie fault lamp on his console, an audible alarm and a yellow TMS level 3 alarm. These alarms only sound in the driving cab. A description of the alarm systems and TMS on the Meridians is given in appendix F. On receiving the red bogie fault lamp and alarm, the driver shut off traction power and began to interrogate the TMS screen to find out the cause of the fault alarm. The driver stated that when he first interrogated the TMS screen, the anomaly displayed was 'hot axle box'. Data derived from the TMS, shows that two alarms were displayed simultaneously, one for a hot axle box and one for a broken cardan shaft.

38 At around 15:48:57 hrs, both wheels of the second wheelset of vehicle 60625 derailed, first the left-hand wheel towards the cess side at 84 miles 60 chains and then the right-hand wheel into the four-foot, 5 chains (101 m) later. Almost immediately after derailing, the wheelset demolished Thorpe Langton foot crossing (figure 4), located at 84 miles 68 chains. Between the start of the irregular marks on the rail head (paragraph 20) and the first point of derailment, a final drive dipstick and two brake pads were dislodged from vehicle 60625.

39 At 15:49:13 hrs the driver applied the brake for 10 seconds, bringing the train speed down to 82 mph (132 km/h) and then, after coasting for 5 - 6 seconds, he reapplied traction power for a further 16 seconds. He consulted the TMS screen and now noticed two anomalies listed, 'hot axle box' and 'broken cardan shaft'.

40 At 15:49:30 hrs, the derailed wheelset struck and demolished the ramp of an AWS magnet located in the centre of the four-foot at 85 miles 60 chains, while the train speed was still around 80 mph (129 km/h). By this time the train's on-board computers had registered several faults consistent with the failure of the second axle on vehicle 60625.

41 At 15:49:41 hrs the fire alarm sounded. This is audible in the driver's cab, the galley and the retail area; in the rest of the train a warble tone is sounded at 3 minute intervals. The driver has stated that he was silencing fault alarms but they were re-sounding and the TMS screen was filling up with messages, the first three of which were 'hot axle box', 'broken cardan shaft' and 'fire'. The OTDR recorded that at 15:49:45 hrs the driver moved the traction controller to the 'coast' position and at 15:49:56 hrs he made a brake application at a setting of around 20% of full service brake. The train speed at this point was 69 mph (111 km/h).

42 At 15:50:02 hrs, a passenger in vehicle 60625 activated the *Passenger Communication Apparatus* (PCA). This caused the emergency brake to apply. The driver immediately overrode the PCA emergency brake application (which he is authorised to do if the brake application would otherwise stop the train in an unsuitable location). He did not establish communication with the passenger, which the PCA would have allowed (discussed at paragraph 178). The fire alarm, which was activated around 21 seconds before the PCA, would have been sounding in the cab at the time.

43 Meanwhile, the driver continued to apply the train brake at between 15% and 35% of full service brake. Train 1F45 then ran over under-bridge 26 (figure 3) and is reported to have showered road vehicles passing under the railway at the time with ballast. Once the train speed was around 14 mph (22 km/h), the driver increased the braking to full (100%) service brake.

44 At 15:50:48 hrs, the train stopped in the cutting with its trailing end located at 86 miles 58 chains. In the 118 seconds between the appearance of the first red bogie fault lamp and the train coming to a stand, the train had travelled around 2 miles 17 chains (3.5 km).

### Actions of on-train crew

45 In addition to the driver, there were four other East Midlands Trains staff on board the train; a train manager, a *customer host* and two other staff.

46 The customer host was in the retail area on the derailed vehicle and became aware of a sustained abnormal noise, impact sounds from under the vehicle and ballast being thrown up. The vehicle was also moving around more than usual and the train appeared to the customer host to take a long time to stop.

47 The customer host tried to contact both the train manager and the driver using the train's intercom system, but she did not get any response. About 70 seconds later she used the intercom system again, but by this time the PCA had already been activated and this disabled the intercom system. The PCA activation would normally have been indicated to the customer host by an audible alarm throughout the train but the prior activation of the fire alarm would have set off an audible alarm in the retail area.

48 The customer host reported that she also pressed the emergency alarm in the retail area[1] but the fire alarm was already sounding by this time. The customer host was not aware the leading end of vehicle 60625 was derailed and therefore did not pull the PCA to alert the driver, believing that the driver would already be aware of and attending to the situation.

[1] This emergency alarm is located behind the counter in the retail area. It sounds in the retail area and the train manager's office.

49 Meanwhile, the other three members of the on-board crew were located near the galley in the leading vehicle and were unaware of events unfolding in the fourth vehicle until the fire alarm sounded (paragraph 41). The train manager then interrogated the TMS screen in the galley of the leading vehicle to locate the emergency and sent the other two members of staff to the fourth vehicle to investigate the report of fire.

50 Internal CCTV footage from the fourth vehicle (60625) shows that passengers were first aware that something was amiss at around 15:48:42 hrs, and articles started to fall from the overhead racks three seconds later. At around the time of the derailment (15:49 hrs), the internal CCTV from the fourth vehicle indicates there was a significant impact followed by a lurch to the left in the direction of travel. The vehicle then appeared to oscillate from side to side and at some point, a right-hand body-side window was struck by an unknown object (likely to have been a piece of ballast) and its outer pane was broken. The passenger who operated the PCA (paragraph 42) and who was reportedly frustrated by the lack of response, returned to his seat.

51 An East Midlands Trains' employee travelling as a passenger in the leading vehicle recalled that approximately 1-2 minutes after passing through Market Harborough Station, the train began to jerk for about 5-10 seconds. There was then a short pause of about 5 seconds before the jerking started again and continued until the train had come to a stop.

## Events following the accident

52 Once the train had come to a stop, the train manager went to the driver's cab to tell him about the fire reported by the TMS system. The driver then opened both of the cab doors and observed smoke coming from the sides of vehicle 60625.

53 At 15:54 hrs he telephoned the signaller at Leicester Power Signal Box to report the situation and to request that both the up and down lines be blocked to traffic so that he could investigate the smoke. The signaller confirmed that running traffic had been stopped.

54 Witness evidence indicates that the driver carried out an inspection of the fourth coach (vehicle 60625), from the cess. He saw that the axle was fractured and the final drive gearbox was lying upside down in the four-foot (figure 7a). The portion of the axle around the fracture, just outboard of the left side of the final drive gearbox (figure 7b) was still glowing orange. He noted that the automatic fire extinguisher system on the vehicle underframe had operated and that the diesel tank had been punctured and was leaking. The driver deployed a hand-held fire extinguisher he had brought with him, onto the hot end of the fractured axle and shut down the engine on the vehicle. He then returned to the cab, made an announcement to reassure passengers, and informed the signaller and East Midlands Trains' control of the situation.

55 The emergency services were notified of the derailment by Network Rail's control centre in Derby at 16:08 hrs. British Transport Police and Leicestershire Police arrived on site at around 16:45 hrs, followed shortly afterwards by the Ambulance Service and the Fire Brigade. The Fire Brigade instructed the driver to stop the engines to minimise risk of fire from the spilled diesel fuel, and temporarily repaired the hole in the fuel tank of the fourth vehicle.

*Figure 7a: Fractured axle as found on site (right-hand wheel side)*

*Figure 7b: Fractured axle as found on site (left-hand wheel side)*

56 The environment on board was difficult for both passengers and crew as they awaited rescue, because the train's power supplies had to be shut down due to the fire risk, leaving no facilities for flushing toilets or making hot drinks. The on-train crew made announcements to keep passengers informed about the situation and the rescue arrangements as best they could. They served refreshments and provided information to the passengers.

57 In the immediate aftermath, East Midlands Trains' control had some initial difficulty identifying when a rescue train would be available and from which direction it would arrive. Passengers could not be detrained until the Fire Brigade had made the site safe (from the spilled fuel) and provided lighting. By 18:15 hrs, a rescue train had arrived on site from Leicester. Evacuation of passengers by the train crew, assisted by the Fire Brigade, began around 18:30 hrs, from the cess side door of the galley in the leading vehicle. By around 19:40 hrs, all the passengers and crew had been transferred to the rescue train and it departed site at around 20:00 hrs.

# The investigation

## Sources of evidence

58 The following sources of evidence were used:

- witness statements and interviews;
- OTDR, TMS, *ORBITA* data and CCTV recordings;
- site photographs, measurements and observations;
- forensic strip down and examination of the failed final drive;
- metallurgical examination and testing of the failed axle, bearing and casing;
- measurements of the failed axle and bearing;
- measurement of other Class 222 axles and bearings;
- mathematical modelling of the final axle failure;
- maintenance records of the failed wheelset;
- history of previous failures of final drives on Meridians and Voyagers;
- previous history of similar final drive failures in the UK and other EU states;
- relevant design, manufacturing and maintenance documentation related to the bogie, gearbox, bearings and axle provided by Bombardier, Voith, Timken and Lucchini;
- literature search of failures resulting from spinning of bearing inner rings (paragraphs 70, 78);
- relevant modules of GE/RT8000 (the Rule Book), Class 222 Operator's Manual, East Midlands Trains driving procedures and training material;
- rig tests of Meridian gearboxes (paragraph 85);
- oil sample histories for the failed gearbox and other Meridian gearboxes (paragraph 132 and 135);
- tests for the presence of ferrous oxides produced by *fretting* on the failed axle (paragraph 84); and
- a review of previous RAIB investigations relevant to this accident.

## Investigation process

59 The RAIB's technical investigation into the causes of the axle fracture was conducted with the assistance of a technical group, set up specifically for this investigation. The objectives of the group were to plan and direct detailed investigation work and discuss emerging evidence.

60 The following organisations were members of the technical group whose meetings were chaired by the RAIB:

- RAIB;
- *Office of Rail Regulation* (ORR), the safety authority;
- East Midlands Trains;
- Bombardier Transportation;
- Eversholt Rail Group;
- Serco (consultant for the initial strip down of the failed gearbox and for the axle investigation, contracted to Bombardier); and
- ESR Technology (consultant for bearing investigation, contracted to Serco).

61 Specifications for forensic work undertaken by consultants in the technical group were drawn up by the group during regular meetings. RAIB engaged other consultants for specific tasks (mathematical modelling, oil analysis and a review of the bearing failure mode) at relevant stages of the investigation.

62 Gearbox testing to investigate the failure mode was undertaken by Voith Turbo in Heidenheim, Germany, under contract to Bombardier and to a test plan agreed with and supervised by the RAIB.

63 Measurements, materials testing, and calculations relating to the output bearings, were undertaken by Timken.

# Key facts and analysis

## Failure mode of the axle

64 Relevant parts of the final drive gearbox and axle are shown in figure 8a (photograph) and figure 8b (schematic). Throughout the following text and associated appendices, the abbreviations 'GE bearing' and 'NGE bearing' are used to denote the gear end and non-gear end tapered roller output bearings[2] respectively. A cutaway of this type of bearing is shown in figure 8c.

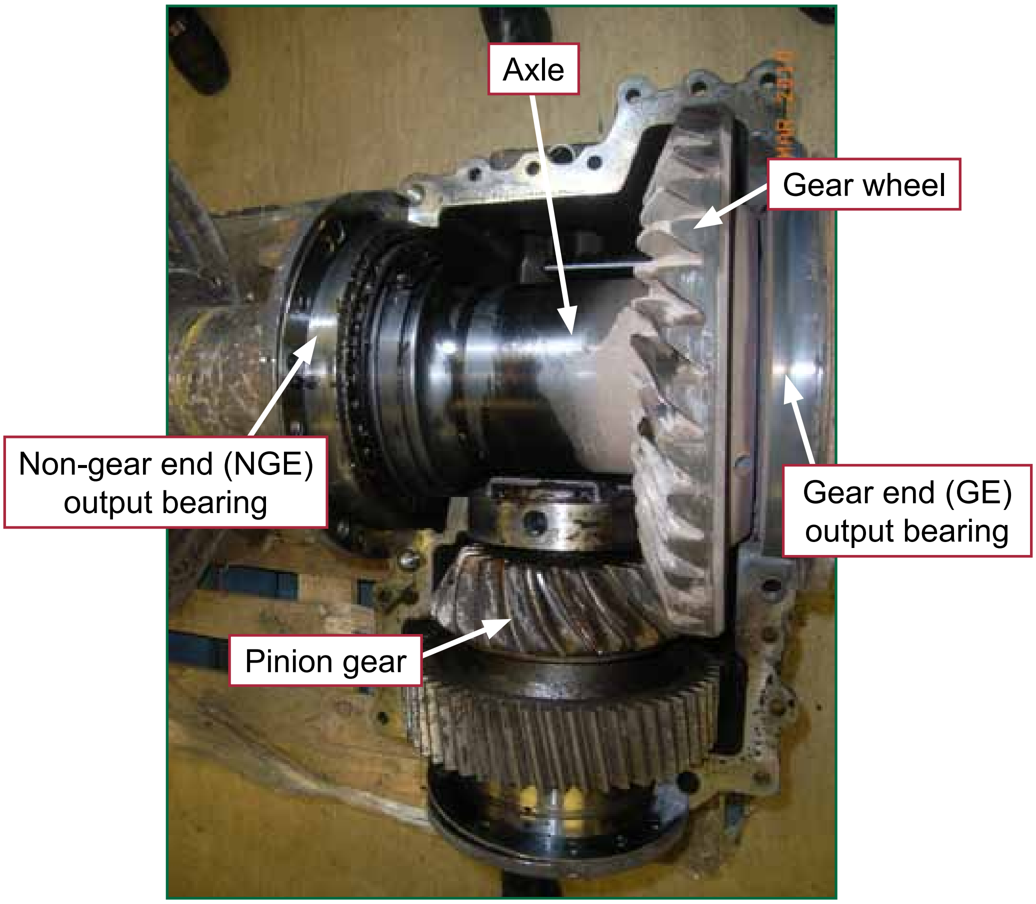


*Figure 8a: Failed final drive gearbox (lower half)*

[2] The GE and NGE bearings work in tandem to carry drive loads in both axial directions but carry radial loads separately. The inner ring of each bearing is fitted to the axle and the outer ring to a bearing housing in the gearbox casing. The rollers, separated by the cage, and lubricated by oil, allow the axle to rotate freely relative to the gearbox.

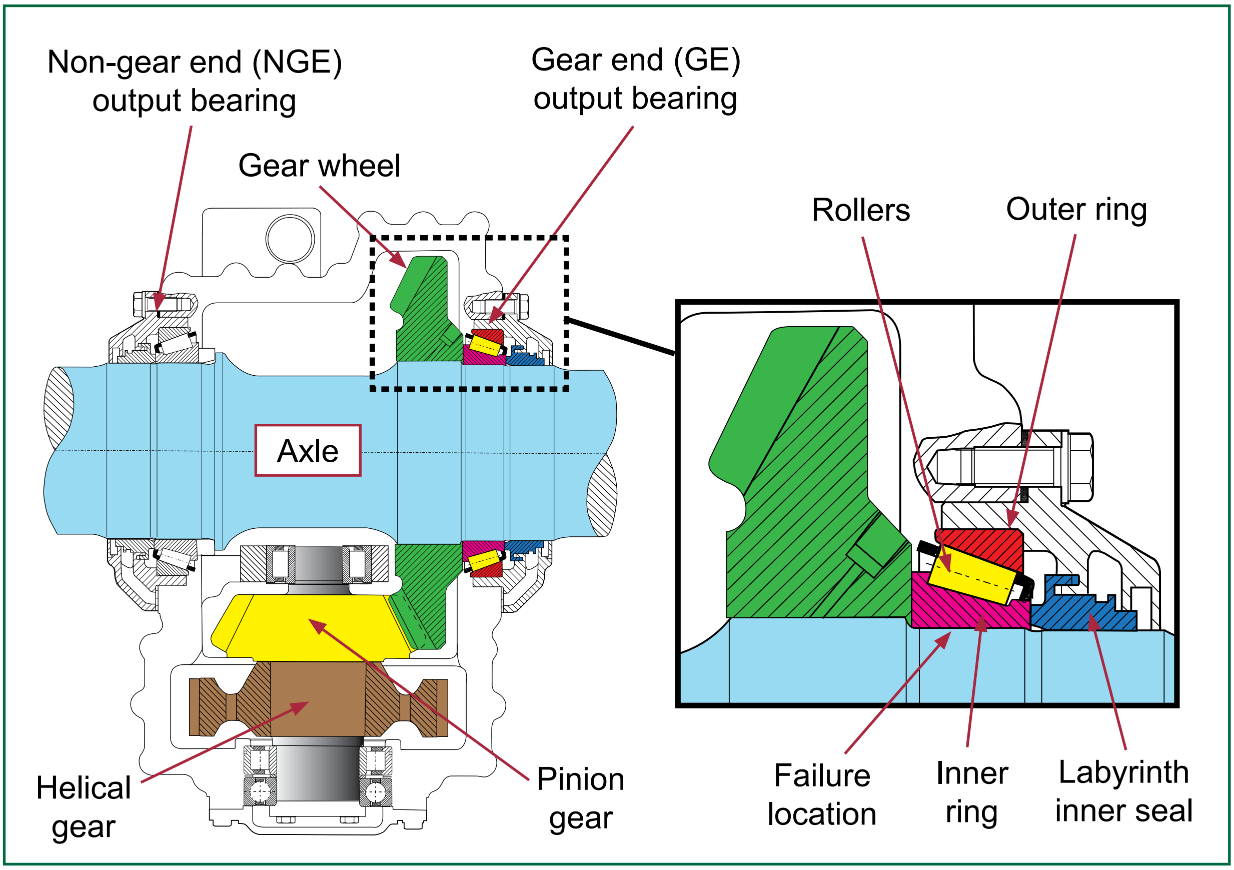


*Figure 8b: Schematic of Meridian gearbox*

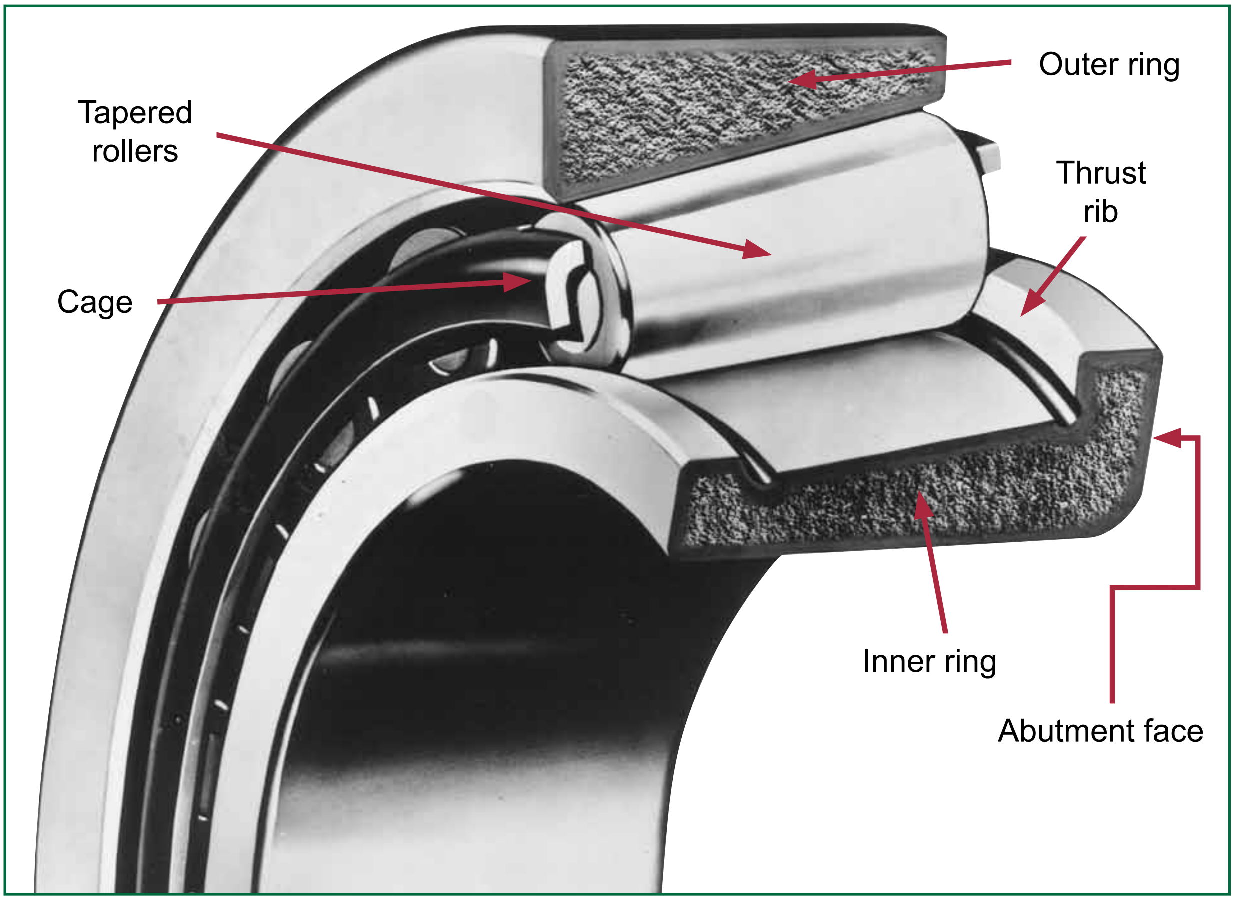


*Figure 8c: Cutaway of generic tapered roller bearing (courtesy of Timken)*

65 At the start of the investigation, the technical group compiled a list of potential failure modes. From this, the modes listed below were identified by the group as requiring detailed consideration and investigation and were tested against the available evidence.

a) Fatigue failure of the axle leading to its fracture.

b) Seizure of the gears leading to axle fracture.

c) Failure of the GE bearing, causing it to become stiff in rotation or seize, leading to spinning of the axle within the inner ring, overheating and fracture of the axle. It was considered whether such a failure could have resulted from:

   i. a defect or damage in the components of the bearing;

   ii. contamination of the bearing with internal debris such as accumulated wear particles;

   iii. incorrect assembly at original manufacture;

   iv. a lack of oil arising from a maintenance error or loss of oil due to puncture of the gearbox prior to the derailment; or

   v. loss of interference or loose fit between the inner ring and axle.

d) *Primary traction rod* failure.

e) Loose bearing housing bolts.

66 There was no evidence to support failure modes a, b, d and e as potential causes of the axle fracture and these were discounted for the reasons given in appendix D. The evidence, as described later at paragraph 69, clearly pointed to failure mode c, the axle fracture having occurred as a result of the axle spinning within the inner ring of the GE bearing. The condition of the GE bearing did not indicate that it had suffered a catastrophic failure; the cage was intact and rollers were still located in their correct radial positions (further details including photographs are provided in appendix D, paragraphs D13 – D17). However, the evidence from the GE bearing indicated that it had become rotationally stiff and had continued to rotate throughout the failure process rather than becoming locked up in a complete seizure. Given the above, the key question during the investigation was which of the initiating causes in modes c(i) to c(v) had caused the GE bearing to become rotationally stiff. As explained in appendix D, detailed examination of the physical evidence did not find evidence to support a failure initiated by defect or damage to the bearing (mode c(i)), contamination (mode c(ii)) or incorrect assembly (mode c(iii)). Although there was no evidence of these initiating a failure, they are known causes of bearing failures generally, and for this reason could not be discounted completely; however they are considered unlikely.

67 Two failure modes remained which required further detailed investigation; a failure due to lack of or loss of oil (mode c(iv)) or a failure with normal oil level due to a loose bearing fit (mode c(v)). Either of these could have initiated a bearing failure and resulted in an axle failure. The RAIB's view from the evidence is that there probably was an adequate oil feed to the GE bearing. The reasons for this view are explained in appendix D (paragraphs D26 - D37) but there are three principal reasons. Firstly, a significant amount of gear oil had been spilled on site after the post-derailment impact with the AWS magnet (paragraph 40). This indicated that the gearbox had been filled correctly at the last oil change (two days prior to the derailment) and that a puncture to the oil sump of the gearbox (appendix D, paragraph D27) had not occurred before the derailment. Secondly, there was no evidence of any blockage in the oil feeds to the GE and NGE bearings. Thirdly, a combination of observations from forensic examinations of the failed gearbox and a comparison of the appearance and extent of damage with other failures caused by running with no oil, indicated that the gearbox had adequate oil at the time of the failure at East Langton.

68 For the above reasons, mode c(iv) was considered an unlikely cause and consequently it is the RAIB's view that the available evidence best supports an axle failure initiated by a loose GE bearing in the presence of oil (mode c(v)). The following paragraphs discuss this failure mode and the evidence which supports it.

## *The cause of the axle overheating*

69 The cause of the overheating and consequent weakening and fracture of the axle was found to be spinning of the GE bearing inner ring relative to the axle. The evidence for this is explained in the following paragraphs. This spinning generated high temperatures by frictional heating, sufficient to cause loss of axle bending strength which resulted in *plastic strain* and fracture. A section through the axle either side of the fracture face is shown in figure 9a; the thinning of the axle either side of the fracture indicates ductile elongation.

70 Although the RAIB has not found any evidence of similar failures where an axle has fractured at the location of a final drive output bearing, in the UK or elsewhere in Europe, there is evidence which indicates that the mode of failure of the axle at East Langton was similar to an axle bearing 'burn-off'. An axle bearing 'burn-off' occurs when spinning of the axle within the bearing inner ring leads to overheating of the axle and, in some cases, to complete ductile fracture of both solid and hollow axles[3,4,5].

71 Metallurgical analysis of the axle material around the fracture faces showed that the highest temperature occurred at the GE bearing axle/inner ring interface, where the temperature had reached around 1100 - 1200°C, and therefore that this interface was the source of the heat. Figure 9b shows the heat affected zones on polished sections through the axles. Figure 9c shows a section through the GE bearing, labyrinth and bearing housing. The heat affected zone in this section is at the bore of the inner ring.

[3] Task force report on the M-2 axle/bearing failure investigation, USA Department of Transportation, Federal Railroad Administration, January 1983.

[4] RAIU report No. 08011001, report into the derailment of a Tara Mines freight train at Skerries on the 10th of January 2008.

[5] ATSB report No. RO-2010-11, 'Derailment of train 3PW4, Wodonga, Victoria', October 2011

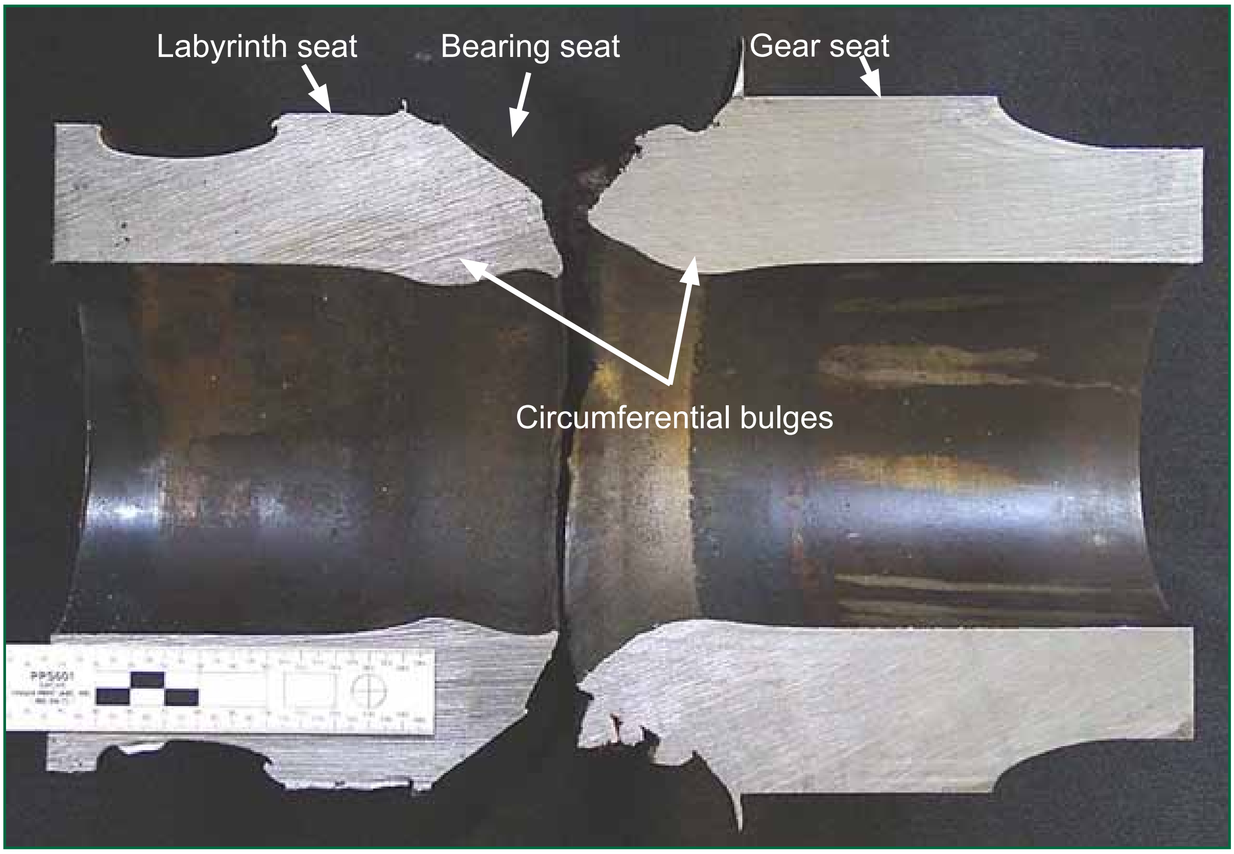


*Figure 9a: Section through axle either side of fracture face (courtesy of Serco)*

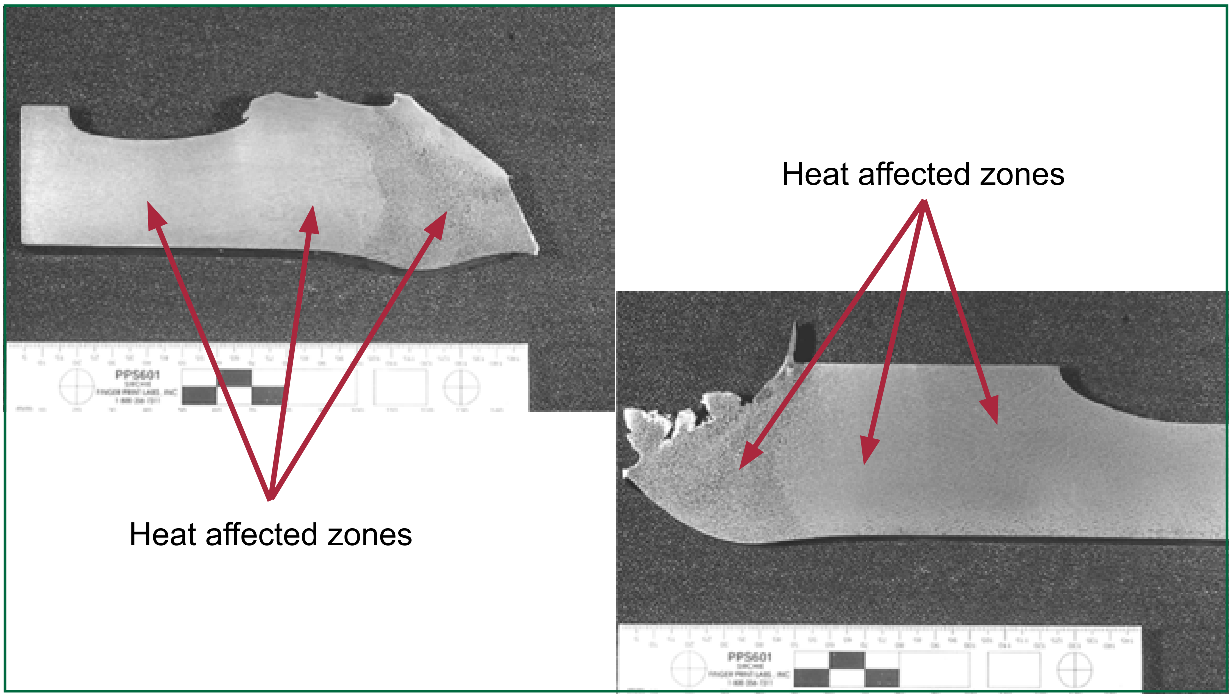


*Figure 9b: Section through each half of axle fracture showing heat affected zones (courtesy of Serco)*

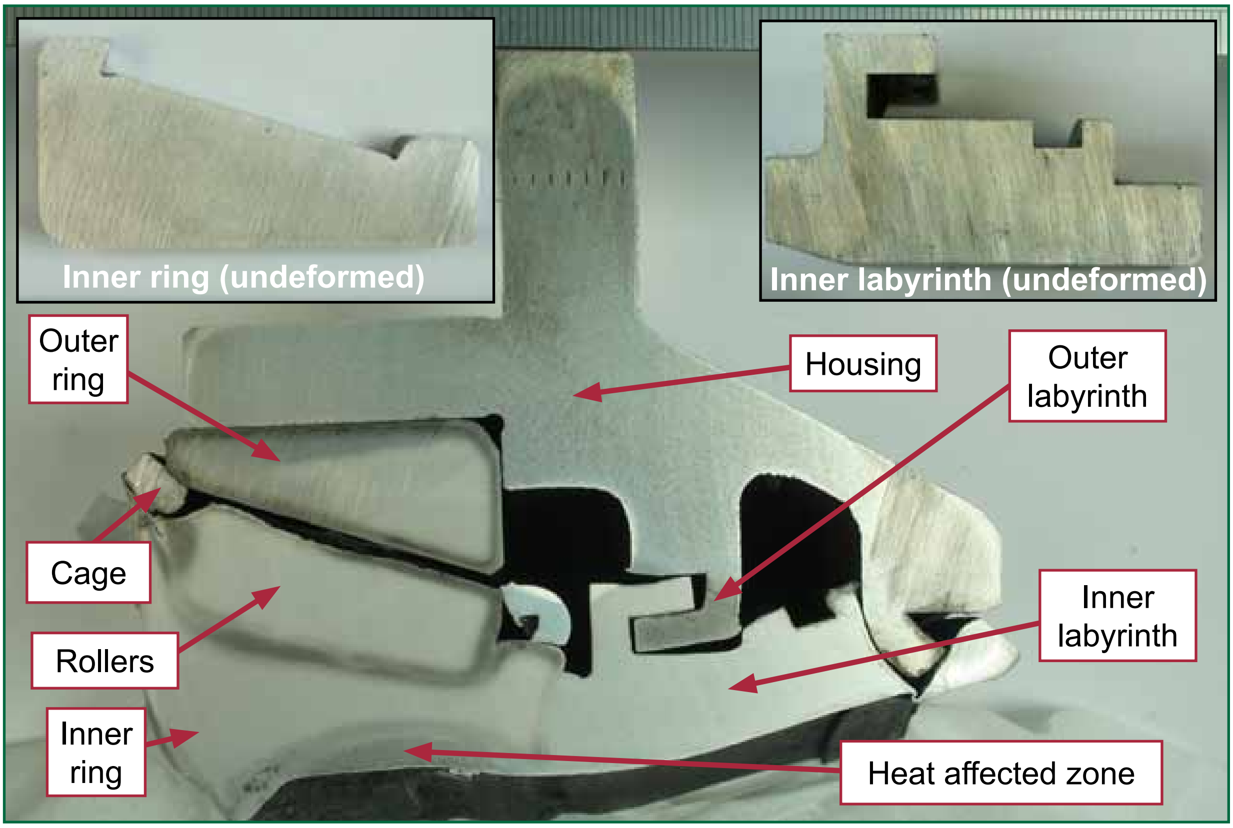


*Figure 9c: Section through output bearing, labyrinth and bearing housing of failed gearbox (courtesy of ESR)*

72 The inner rings of both output bearings should have an *interference fit* on the axle and should not slip relative to the axle during operation. However, if the ring does not have an adequate interference fit on the axle and the bearing becomes rotationally stiff for some reason (discussed later at paragraph 77), then spinning and frictional heating can occur at the interface between them. The heat input at this interface, when the axle is rotating and rubbing against the inner ring, is dependent on three main factors, none of which remain constant with time.

- The relative rotational speed between the axle and inner ring, which can vary from zero to full axle rotational speed at 100% slip.
- The bearing radial loads, arising from inertia loads on the gearbox and drive loads from meshing of the gears.
- The sliding friction coefficient at the interface which depends on the condition of the rubbing surfaces, the presence of any lubricant and temperature. It can vary from around 0.09[6] (lubricated steel on steel at room temperature) to around 0.6[7] (unlubricated steel on steel at temperatures of 600 - 700°C).

Taking a relatively low friction coefficient of 0.15, it can be shown that at a train speed of 94 mph (151 km/h) and with 100% rotational slip, a heat input of around 30 kW could be expected. If the friction coefficient was higher, the same heat input could occur at less than 100% slip.

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6 http://www.engineershandbook.com/tables/frictioncoefficients.htm

7 Wang H, Conry T, Cusano C, 'Effects of cone/axle rubbing due to roller bearing seizure on the thermomechanical behaviour of a railroad axle' Journal of Tribology, Vol 118, April 1996.

73 Thermal analysis of the hollow Meridian axle under spinning inner ring conditions, for a range of heat inputs, was undertaken to determine the time taken to reach a temperature of around 1100 -1200°C at the axle/inner ring interface. In the area of the output bearing seats the diameter of the hollow axle is nominally 200 mm and the internal bore is 110 mm (ie a tube wall thickness of 45 mm). The following times were obtained:

- 30 kW: 12 mins
- 15 kW: 60 mins
- 7.5 kW: maximum temperature reached 550°C

74 Figure 10 shows the calculated temperature distribution around the axle/inner ring interface after 12 minutes for a heat input of 30 kW. By this time the outer surface of the axle would be expected to have reached around 1100°C, and the inner surface around 650°C. At these temperatures, the strength of the axle material is likely to have been between 5% (outer surface) and 24% (inner surface) of its strength at room temperature[6]. While some of the heat input is lost from the axle/inner ring interface (mainly by conduction into cooler parts of the axle), a stage would have been reached when the temperature throughout the thickness of the axle was high enough for gross plastic strain, ductile thinning of the weakened material (paragraph 69) and fracture to occur.

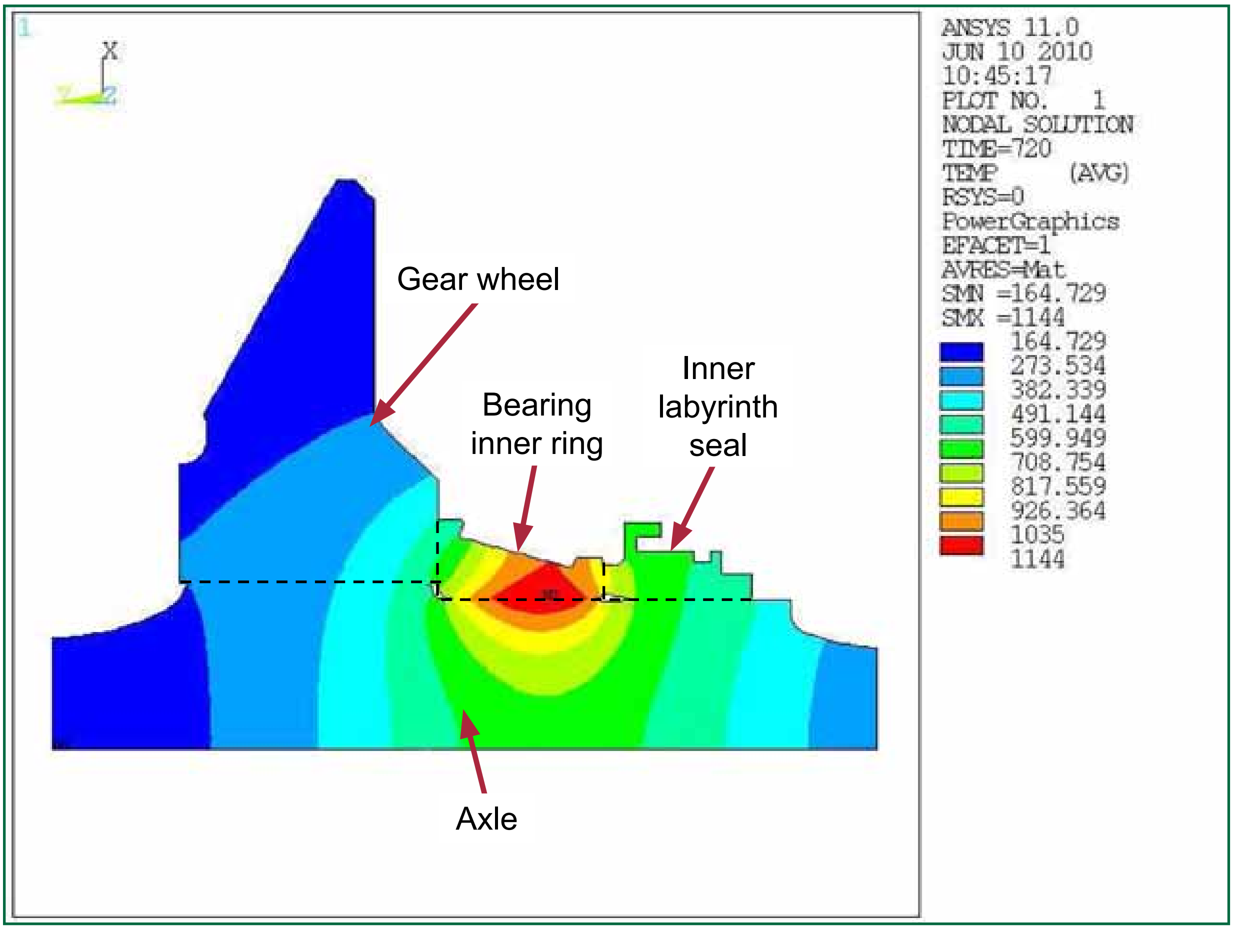


*Figure 10: Calculated temperature distribution at axle/inner ring interface after 12 mins with 30 kW heat input (courtesy of Interfleet Technology)*

75 The time taken to final fracture is dependent on the rate of heat input and the stresses on the axle, which are likely to have been varying during the approach to final fracture. If the rate of heat input remained at a constant 30 kW, final fracture would be expected to occur no more than a few minutes after the axle/inner ring interface first reached 1100°C - 1200°C. At lower values of heat input, the time taken for the axle to reach the point of fracture would be expected to be longer.

76 The thermal analysis model was re-run with a solid axle of the same external geometry as the hollow axle to see how much longer a solid axle would take to fail under a constant heat input of 30 kW. This confirmed that a solid axle could also suffer a fracture as a result of a spinning bearing inner ring and that the time taken to fracture would not be expected to be significantly longer than for a hollow axle.

*Cause of the spinning inner ring*

77 The cause of the GE bearing inner ring spinning on the axle could not be deduced from the physical evidence of the damaged components alone. It was clear from the evidence (paragraphs 71 - 73) that a high relative slip speed had developed between the inner ring and axle during the failure. The only plausible way this could have occurred was for the bearing to have stiffened sufficiently such that the torque required to rotate the bearing was higher than that required to slip the axle within the inner ring. Failure of the GE bearing due to an inadequate supply of oil or a bearing failure due to fatigue or some other bearing defect was considered unlikely for the reasons given in appendix D. Another possible explanation was that the spinning had been caused by a stiffening of the GE bearing due to a loss of interference fit between the inner ring and axle. This type of bearing failure has been found on axle bearings which have been adequately lubricated, and has led on some occasions to complete fracture of the axle. Some research has previously been carried out on this type of failure mode, as explained below.

78 Nagatomo and Toth[8] investigated the damage progression of a bearing from a loose fit towards imminent failure. They studied the failure sequence of a pair of grease lubricated 120 mm bore tapered roller axle bearings from a Shinkansen high speed train, by instrumented testing. The outboard bearing was fitted to the axle with zero interference[9] and the inboard bearing with its normal interference fit (68-102 μm). A static vertical load of 110 kN was applied to the pair of bearings to represent the average service loads and the axle was rotated at a speed of 1852 rpm. During the test, the rotation of the bearing inner ring with zero interference gradually increased in speed, relative to the axle, from a very slow circumferential slip (called *inner ring creep*) to progressively faster rotation (up to 25 rpm) as the clearance increased due to wear. Between 500 μm and 1500 μm of clearance on diameter, it was noted that the running temperature rose and fluctuated up to peaks of around 150°C, sufficient to affect the lubrication of the bearing and deterioration of the grease. There was also an increase in vibration levels, indicating that the clearance was affecting the operation of the bearing. At the end of the test, the bearing was smoking and noisy and was deemed to be approaching thermal failure.

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[8] Nagatomo T and Toth D; 'Investigation of the bearing damage progression starting from cone creep of a railroad axle journal bearing', QR of the RTRI, Volume 47, No. 3, August 2006.

[9] Railway axle bearings are normally fitted with a specified amount of interference between the shaft and bearing inner ring so that the inner ring is clamped tightly onto the shaft. At zero interference, there is no clamping pressure between the shaft and inner ring.

79 The research of Nagatomo and Toth[8] indicated that a loss of interference between the axle and inner ring of the GE bearing could result in a clearance developing between the inner ring and axle due to wear. If allowed to continue unchecked, the clearance would become larger. The research also identified that as the clearance increased, the bearing began to suffer variations in temperature which were much higher than in normal operation and abnormal vibration. Eventually this could lead to lubrication breakdown and potentially, a thermal runaway[10], at which point the bearing torque would be expected to rise significantly and the bearing could cease to rotate freely.

80 There are some key differences between the bearing set-up in the above research and the Meridian gearbox, such as bearing size, type of lubrication, loading, running speed and spacing of the bearing pair. Therefore, as part of this investigation, laboratory tests were undertaken to investigate the effect of having an axle/inner ring clearance on the Meridian gearbox. These tests are described at paragraphs 85 to 92.

81 Some other reports[3,5,7] have also linked the failure of railway axle bearings to loss of interference fit on the axle, sometimes leading to axle fracture. Axle or shaft failures resulting from a loose bearing fit are not confined to railway axle bearings. A paper published in February 2010[11] reported on a failure investigation of a fan shaft driven by a 4.1 MW electric motor and running up to 744 rpm, which had melted under one of two roller bearings supporting the shaft. That failure was attributed to a loss of interference fit and a clearance which developed between the bearing and the shaft.

*The discovery of GE bearings in service with axle/inner ring clearances*

82 Since evidence about the fit between the axle and inner ring of the failed bearing at East Langton was destroyed in the accident, the condition of other axles in service was investigated. During the course of the investigation, ten Meridian powered axles were removed from service due to higher than average oil contamination, discoloured oil, or being of similar age to the failed axle. Of these, six powered axles with mileages between 673,000 and 1.2 million (1.1 - 1.9 million km) were found to have either low interference or a clearance at the axle/inner ring interface. Details of these axles are given in table 1. Equipment used to measure axle and inner ring bore dimensions in this investigation was calibrated to an accuracy of +/- 2 μm.

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[10] Thermal runaway: a situation where overheating of the bearing leads to a breakdown of lubrication and further escalation in temperature as the bearings are pushed into a *preloaded condition*.

[11] M. Ristivojevic, R. Mitrovic, T. Lazovic 'Investigation of causes of fan shaft failure', Engineering Failure Analysis 17 (2010) 1188–1194, Elsevier.

83 The first two axles in table 1 were found to have significant fretting, confined mainly to the bore of the inner ring, and evidence of the early stages of creep between the inner ring and axle. The other four axles were found to have axle/inner ring clearances of up to 79 µm at the GE bearings. The inner rings on these axles had been creeping on the axle (figure 11), resulting in wear to both the axle and inner ring bore and clearances at the interfaces. On the bearing inner ring of wheelset E1604/10, there were regular scroll marks on the abutment face made by a piece of hard material caught between this face and the gear wheel. From these marks the maximum rate of creep of the inner ring relative to the axle and gear wheel was estimated to have been 0.22 mm per revolution. These observations were consistent with those described in Nagatomo and Toth[8]. None of these axles with clearances showed signs of overheating but they did have abnormally dark oil. Had they not been removed from service for the reasons given in table 1, it is possible that some of them could have progressed to failure.

*Figure 11: Final drive from wheelset E1604/58 after strip down, showing wear on bearing seat due to inner ring rotation*

| Axle No. | Mileage at removal (reason for removal) | Average GE bearing seat diameter (mm) | Average GE bearing inner ring bore diameter (mm) | Interference (mm) |
|---|---|---|---|---|
| E1847/20 | 673,151 (stiff axle box bearing) | 200.005[12] | 199.986 | 0.019 (interference) |
| E0400644/45 | 974,864 (routine overhaul) | 200.006 (gear wheel fitted) | 199.995 | 0.011 (interference) |
| E1847/34 | 1,060,856 (abnormal oil sample) | 199.978 (gear wheel fitted) | 200.055 | - 0.077 (clearance) |
| E1604/58 | 818,105 (abnormal oil sample) | 199.970 (gear wheel fitted) | 200.049 | - 0.079 (clearance) |
| E1604/10 | 1,035,304 (brake disc wear) | 199.979 (gear wheel fitted) | 200.051 | - 0.072 (clearance) |
| E0400644/28 | 1,121,697 (abnormal oil sample) | 199.984 | Not measured | Not known |

*Table 1: Service axles found with low interference or clearance at the axle/inner ring interface of the GE bearings*

84 On those axles with axle/inner ring clearance at the GE bearing, a large amount of reddish brown fretting debris (a particular rust-like oxide of iron called ‘$\alpha Fe_2O_3$’ which is produced when fretting of ferrous material occurs) had also been generated at the interface between the inner ring and axle. It coated the bearings and axle surfaces and changed the colour of the gearbox oil. The investigation explored whether there was a link between the presence of a coating of $\alpha Fe_2O_3$ on the axle surfaces (which are not subject to direct fretting contact) and the presence of an axle/inner ring clearance. The failed axle was tested for the presence of $\alpha Fe_2O_3$. Material was scraped off the axle surface between the output bearings (this area had been damaged by heat and coated in a hard carbon deposit) and tested positive for $\alpha Fe_2O_3$. However, control tests on five other axles which did not have a clearance at the GE bearing seat, also tested positive for $\alpha Fe_2O_3$ and therefore it was not possible to conclude that the result obtained for the failed axle provided firm evidence that there had been an axle/inner ring clearance.

### *Investigation of the effect of axle/inner ring clearance on the potential for bearing failure*

85 Testing was undertaken to understand the effect of a clearance between the axle and inner ring of the GE bearing on the behaviour of the Meridian gearbox, and to see if such a clearance could have led to a failure of the GE bearing.

[12] This is an estimated minimum value. The seat diameter was measured at 200.043 mm with the gear wheel removed. No measurement was made with the gear wheel fitted. Therefore a maximum 38 μm allowance is made (paragraph 106) for the shrinkage of the bearing seat due to fit of the gear wheel.

86 Three gearboxes were used for the testing, with axle/inner ring clearances of 77 µm (gearbox 1), 1558 µm (gearbox 2) and 477 µm (gearbox 3). Gearbox 1 was as found in service (table 1, axle E1847/34 refers). The GE bearing seats on the axles of gearboxes 2 and 3 were machined to obtain clearances close to target values of 1500 µm and 500 µm. Two additional objectives of the tests were:

- to check how oil samples from the test gearboxes vary depending upon when they are taken, both as an input to the investigation and to provide information to Bombardier regarding the Meridian oil sampling regime; and
- to check that the fusible plugs fitted to the Meridian and Voyager fleets after the East Langton derailment (paragraph 197) would provide adequate warning to the driver of an impending failure of the final drive output bearings.

Details of the test rig, instrumentation and key results are given in appendix E. The test gearboxes were subsequently stripped down at Bombardier's overhaul facility in Crewe, UK and witnessed by the RAIB.

87 Test gearboxes 1 and 2 exhibited a generally stable performance and demonstrated that even a large clearance between the axle and GE bearing inner ring (gearbox 2) does not automatically lead to a bearing failure. The tests also indicated that these gearboxes were tolerant of an over-fill of oil (7 litres compared to the normal 5 litres) and under-fill down to 2 litres (tested on gearbox 2 only). There was no evidence of high temperatures or unstable behaviour at any of these oil levels. The oil volume had to be reduced to around 1 litre to provoke a bearing failure.

88 However, the performance of gearbox 3 indicated that even with normal oil levels, a gearbox with an axle/inner ring clearance can behave in an unpredictable manner, such that the GE output bearing temperature rises rapidly and/or reaches a high running temperature. Two incidents with test gearbox 3 demonstrated this:

a) While running at 1200 rpm without load, in its first commissioning test on the rig, gearbox 3 suffered excessive vibration and a rapid rise in GE bearing temperature (appendix E, figure E5). The peak temperature had only reached 57°C when the test had to be aborted. When the bearing was stripped down, there was evidence (in the form of discolouration of the inner ring and rollers) that it had overheated. This indicated that the actual temperatures within the bearing had been much higher than those measured by the instrumentation. There was also evidence of damage to the surface of the axle around a temperature measurement hole drilled for the tests, indicating that the inner ring had been moving round on the axle. The data also showed that the temperatures of both output bearings had risen simultaneously (although the peak NGE bearing temperature was 19°C lower), indicating the bearings had entered a preloaded condition which had caused the observed temperature rise (discussed further at paragraph 91).

b) With a new GE bearing fitted (estimated axle/inner ring clearance of 474 μm) and while running at 3000 rpm with the cooling fan switched on[13], the GE bearing outer ring temperature rose abnormally and peaked at 143°C (appendix E, figure E6). There was also a simultaneous rise in the NGE bearing outer ring temperature, indicating the bearings had again entered a preloaded condition. At this point in the test there was a failure of the instrumentation measuring the GE and NGE inner ring temperatures and the test was stopped for repairs. When the test was repeated the following day, the GE bearing temperature did not exceed 96°C. The difference in peak outer ring temperature between consecutive runs was almost 50°C, and confirmed that the incident on the previous day had been an abnormal and unpredictable event. The rotational speed at which this incident occurred was within the design operating envelope of the gearbox.

89 The significance of the high bearing temperatures seen in these incidents is that the additional heat could increase the temperature differential between the inner and outer rings and lead to more preloading of the bearings. This would cause the temperature to increase further[14] and the viscosity of the oil to reduce, until a breakdown of lubrication occurs at the thrust rib (figure 8c). These changes could then further increase the bearing temperature, leading to a thermal runaway, which then causes the bearing to become rotationally stiff.

90 Because of the limitations of the test rig, it was not possible to introduce acceleration shocks on the gearbox while running, or to blow cold air over the casing, to simulate actual Meridian service operating conditions. These additional factors would be expected to exacerbate the unpredictability of the behaviour of a degraded gearbox running with an axle/inner ring clearance, for two reasons. Firstly, the presence of shock loading is likely to increase the chance of rollers skewing and jamming. Secondly, increased cooling on the casing tends to increase the temperature differential between the outer ring of the bearing (which is in contact with the casing) and the inner ring on the axle. This in turn causes increased expansion of the inner ring relative to the outer ring and increases the probability of the degraded gearbox entering an excessively preloaded condition. For this reason, a degraded gearbox would be expected to be most vulnerable in cold conditions.

[13] The cooling fan passes air over the gearbox on the test rig. While this does not accurately represent the airflow over the gearbox when running on a train, it does allow the effect of wind cooling of the gearbox casing to be explored on the test rig.

[14] The temperature rise is due to the increased heat generation within the bearing when running in a preloaded condition.

91 The precise reasons for the observed rapid temperature rises (paragraph 88) could not be determined directly from the test data, since it was not possible to monitor the relative rotation between the inner ring and axle and relate this to the observed temperature changes. However in both cases the temperature data indicated that the bearings had entered a preloaded condition. Under normal operating conditions, it is estimated by the bearing manufacturer that the GE bearing inner ring would typically run 10°C hotter than the outer ring. This temperature differential causes expansion of the inner ring relative to the outer ring which is a normal condition and gearboxes are built with an amount of axial clearance (called 'end float') to accommodate this. If the temperature differential increases further, the bearing will start to go into preload and the amount of heat generation increases rapidly. Three factors which could have increased the vulnerability of gearbox 3 to preload are:

- Cooling of the casing (which holds the outer ring of the bearing) when the cooling fan was switched on, as explained at paragraph 90.
- Rotation of the GE bearing inner ring (due to the axle/inner ring clearance) which is likely to have created frictional heating between the inner ring and the axle. This also would tend to increase the differential temperature between the bearing rings.
- Reduced thermal conductivity between the inner ring and axle due to the gap caused by the clearance, resulting in a higher inner ring temperature and greater temperature differential between the rings.

92 Although there were no total failures of any of the test gearboxes when running with normal oil levels, the tests demonstrated that the presence of an axle/inner ring clearance at the GE bearing (which was the only abnormal feature of these test gearboxes) introduces a vulnerability into the gearbox which has the potential to cause excessive bearing temperatures.

## Identification of the immediate cause[15]

**93 The immediate cause of the derailment was the overheating and subsequent fracture of the powered trailing axle of the leading bogie of the fourth vehicle in the train. This led to the unsupported left-hand wheel *flange climbing* the rail to the cess (left-hand) side and the right-hand wheel dropping into the four-foot of the down line.**

94 There was no evidence of any track, wheel or vehicle suspension related failure which could have caused the axle to fracture.

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

## Identification of causal[16] factors and contributory factors[17]

95 It should be noted that with the destruction of key evidence around the GE bearing during the failure, it was not possible to be absolutely certain about the cause of the GE bearing ceasing to rotate normally. Consequently, the review of the evidence and the analysis involved an assessment of the probability of different possible failure modes. The factors described in the following sections reflect the RAIB's view of the most likely way in which the failure occurred. The reasons why the RAIB considers that alternative explanations are unlikely or can be discounted are described in appendix D.

96 The investigation identified five factors, related to the overheated axle, which are discussed in the following paragraphs. The first ((a.) below) is proven by the evidence, the others are based on the RAIB's view that the most likely cause of the axle fracture was an undetected loose fit of the GE bearing, which could not be proved conclusively, due to the loss of key evidence in the failure.

a. spinning of the GE bearing inner ring on the axle;

b. insufficiency of the interference fit between the GE bearing and axle at manufacture;

c. size of the bearing seat on the axle;

d. progressive loss of bearing interference fit in service; and

e. the maintenance regime for the Meridian gearboxes.

Spinning of the GE output bearing inner ring on the axle

97 **The spinning of the bearing inner ring on the axle led directly to the axle fracture and was a causal factor.**

98 As explained at paragraph 69, the cause of the axle overheating and subsequent fracture was the output bearing inner ring spinning on the axle. At some stage shortly before the axle overheated, the bearing stopped rotating freely, (ie it became stiff) though not as a result of a sudden bearing seizure. Once this happened, virtually all relative rotation between the axle and GE bearing occurred between the inner ring and axle, instead of between the inner and outer rings of the bearing by means of the rollers. As this relative rotational speed increased towards 100%, there would have been an increasing frictional heat input to the axle.

99 The time taken to heat an axle, by the spinning of the GE bearing inner ring, to a temperature at which it could no longer carry normal service stresses is dependent on the amount of heat input. As explained at paragraph 73, the time for the axle to initially heat up to the peak temperatures observed from the evidence could be around 12 minutes for a heat input of 30 kW, with final fracture expected shortly after the peak temperature was reached. At lower levels of heat input, the time to fracture would be longer.

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

[17] Any condition, event or behaviour that affected or sustained the occurrence, or exacerbated the outcome. Eliminating one or more of these factors would not have prevented the occurrence but their presence made it more likely, or changed the outcome.

## The relationship between inner ring spinning and axle/inner ring clearance

100 While the spinning of the GE bearing inner ring on the axle was positively identified as the cause of the axle fracture (paragraph 69), the stages leading up to this spinning condition could not be established with certainty, due to the destruction of the GE bearing and its seat on the axle during the failure. In particular, the presence of a clearance at the axle/inner ring interface could not be confirmed. However, the RAIB considers it is likely that such a clearance existed and gave rise to the spinning inner ring for the following reasons:

- Other Meridian axles have been found with axle/inner ring clearances since the East Langton failure (table 1), some using detection criteria developed after the failure (paragraph 82). Additionally, a probabilistic analysis of the tolerances on the fit of the GE bearing (described later at paragraph 124) indicates it is likely that other axles could also have developed a loose fit.
- There is evidence from the oil sampling data (paragraph 135) which indicates that the failed axle had probably generated higher levels of ferrous metal wear product during its life compared to other axles found with a clearance. These levels are significantly higher than those generated in gearboxes without a clearance at the GE bearing.

101 The RAIB considers that an axle/inner ring clearance at the GE bearing, could have led to a failure of that bearing at East Langton for the following reasons:

- The test results (paragraphs 91 and 92) suggest that an axle/inner ring clearance could lead to increased preload and an overheating GE bearing and potentially a thermal runaway. Such overheating is likely to have caused the bearing torque to increase significantly and the bearing to become stiff in rotation, which would then have caused the axle to spin relative to the inner ring.
- Bearing failures due to loose fits have generally been linked with railway axle bearings[3,5,7,8], which in some cases have resulted in axle fractures. Bearing failure has arisen from a loss of fit or clearance in a non-railway application[11], which indicates that such failures are not confined to the specific geometries of railway axle bearings.
- Other bearing failure modes which could also have given rise to a spinning inner ring, such as a bearing seizure due to a defect or oil starvation, are not supported by the available evidence, as explained at appendix D.

The following paragraphs explain the factors that are likely to have led to the spinning inner ring, and the supporting evidence.

## The interference fit between the GE bearing and axle was insufficient at manufacture

102 **The interference fit of the GE bearing inner ring onto the axle at manufacture is likely to have been significantly less than the minimum level intended in the design, because of the effect of the adjacent gear wheel fit on the hollow axle. This was probably causal.**

103 The design intent was that the inner rings of both the GE and NGE bearings would have an interference fit onto the axle of 75 -120 µm.

104 However, the adjacent gear wheel (figure 8b), which is assembled onto the axle before the bearing, has a heavier interference fit onto the axle of 243 - 309 µm. The Meridian axle has a relatively thin wall compared to other hollow railway axles and the installation of the gear wheel caused the adjacent bearing seat on the axle to shrink below the minimum axle diameter necessary to achieve the correct (design) fit of the GE bearing.

105 This shrinkage was confirmed by both calculation and measurement. Mathematical modelling of the Meridian axle, gear wheel and GE bearing indicates that between 24 and 30 µm of shrinkage on diameter (12-15 µm on radius) could occur at the centre of the bearing seat, depending on the level of interference between the gear and axle (figure 12). Another effect of the gear fit is that it causes the bearing seat to be tapered (figure 12); the inner edge of the seat closest to the gear wheel shrinks more than the outer edge. The corresponding amount of bearing seat shrinkage for a solid axle (figure 12) would be significantly lower at between 5 and 10 µm on diameter. Measurements carried out on a sample of four Meridian bearing seats, with and without the adjacent gear wheel fitted, indicated an average amount of shrinkage of 27 µm on diameter and a range of 21 - 38 µm.

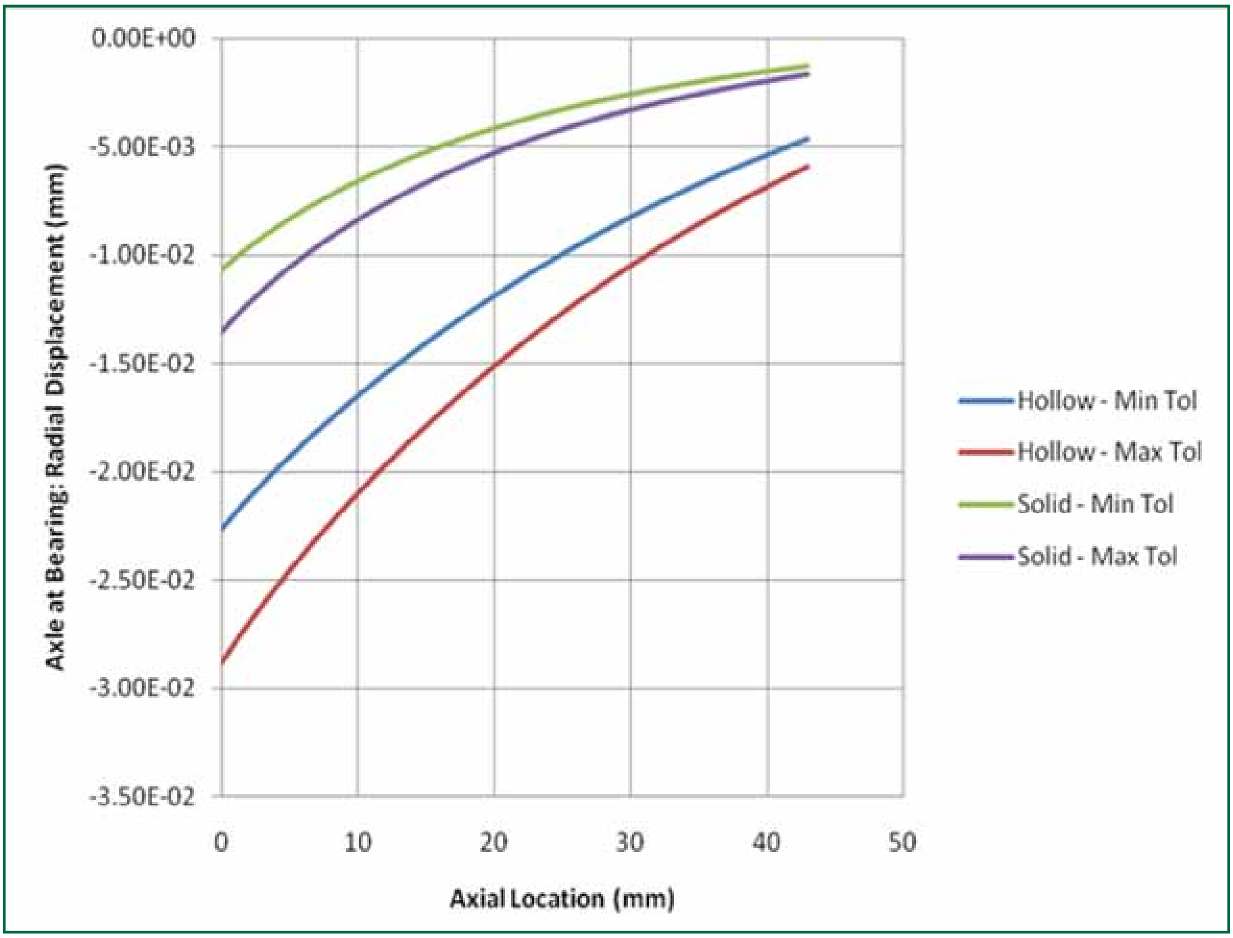


*Figure 12: Calculated radial displacement of gear-side output bearing seat for Meridian (hollow) axle and equivalent diameter solid axle (courtesy of Interfleet Technology)*

106 The effect of this shrinkage is to reduce the interference fit of the GE bearing on the axle. Within a population of gearboxes, the minimum interference fit could be reduced from the minimum design value of 75 μm to 37 μm (taking the maximum measured shrinkage of 38 μm). It was not possible to determine what the interference fit of the GE bearing inner ring was on the failed axle when it was new because the bore size of the inner ring is not known. However, the evidence indicates that, like some other axles discussed at paragraph 82, it could have lost around half the minimum intended interference due to the adjacent gear fit. This reduction in interference is significant and would have left the bearing inner ring vulnerable to eventually becoming loose, due to other factors which are discussed below.

### Size of the GE bearing seat on the axle

107 **The GE bearing seat on the axle may have been manufactured undersize and this went undetected. This was a possible causal factor.**

108 The GE bearing seat was damaged in the accident and therefore no measurement of its size could be made. However, measurements of the NGE bearing seat on the same axle showed it to be undersize and tapered, varying from 200.010 mm at the outboard end to 200.041 mm at the inboard end. The diameter of the seat should have been in the range 200.050 - 200.070 mm. The measurement recorded by Lucchini at manufacture was 200.055 mm. Examination of the NGE bearing seat showed the original grinding marks to be largely intact, indicating that it was not wear that had caused the seat to become undersized. The NGE bearing seat had been subject to abnormal temperatures during the short duration of the failure of the GE bearing, but metallurgical tests indicated that the temperature had not exceeded 350°C. At this level of temperature there would not have been sufficient loss of material strength for the applied interference pressure (even at the maximum interference fit) to shrink the axle in the area of the NGE seat by a measurable amount. These findings indicated that the NGE bearing seat may have been manufactured undersize.

109 Lucchini reports that the failed axle (E1692/07) was manufactured in 2004 as part of a cast of 34 axles. One of these was used for material testing, another was scrapped following visual inspection and the remainder were passed fit for service. Lucchini reports that its practice before 2007 was in accordance with the applicable international standard (EN13261:2003: Railway applications. Wheelsets and bogies. Axles. Product requirements) for such measurements. However it did not have a specific company procedure for the dimensional checking as it does now. It has not been possible to ascertain precisely what dimensional checking procedure was used on axle E1692/07; however Lucchini reported that final dimensional quality checks would have been undertaken using a micrometer and that the accuracy of the geometry checking process would have been around +/- 5 to 10 μm.

110 The measurement recorded by Lucchini for the GE bearing seat diameter at manufacture was 200.060 mm. Although an undersize NGE bearing seat does not prove that the GE bearing seat was also manufactured undersize, it does indicate the possibility that there was some anomaly with this axle and that an undetected error in manufacture could have passed through subsequent quality control procedures.

111 Voith did not carry out any checks on the dimensions of the output bearing seats when it received the axle from Lucchini because it accepted them as compliant with the design, as declared by Lucchini. Therefore, any bearing seats which may have been undersize would not have been detected by Voith and rejected during the assembly of the gearbox onto the axle.

## Progressive loss of bearing interference in service

112 **There would have been a gradual increase of the bearing bore, which progressively reduced the GE bearing interference over the life of the gearbox. This was a probable causal factor.**

113 The failure at East Langton occurred after the gearbox had run 922,000 miles (1.48 million km) in service. This indicated that the bearing interference fit when the gearbox was new was not sufficiently low to have caused failure, and that some other time dependent factor was also involved. Two separate mechanisms for increasing bearing bore diameter were identified.

114 The first mechanism is inner ring growth which is a known phenomenon that can affect the dimensional stability of a bearing. The inner ring expands during its operational life such that there is a reduction in the interference fit. Allowance is made for this bore growth in the interference fits recommended by the bearing manufacturer, up to the appropriate maximum for each type of bearing (20 µm in the case of this 200 mm bore bearing). Specialists advising the investigation have stated that the mechanism of inner ring growth is not well understood because it depends on many variables, but research has identified three key factors which affect it:

- The metallurgy of the inner ring, in particular the content of retained austenite[18] (a specific crystalline form of iron that is not stable at room temperature). The greater the amount of retained austenite, the greater the potential for its transformation into martensite, which involves an increase in volume and corresponding increase in bore diameter. Retained austenite is desirable in bearing steels to provide material toughness and improve bearing life. The amount of retained austenite in a bearing steel has to be controlled during manufacture to achieve a balance between its beneficial effects and minimising dimensional instability.
- The bearing operating temperature and time at that temperature. The higher the temperature and longer the time, the more transformation of retained austenite would be expected to occur.
- The loading of the bearing. The higher the loads carried by a bearing, the higher are the stresses on the *raceway* of the inner ring and this leads to a greater transformation of retained austenite.

115 The second mechanism is wear caused by fretting, which also reduces the bearing interference fit. If the interference fit of a bearing on an axle is correct, there should not be any significant fretting wear at the axle/inner ring interface over the design life of the component. However, several Meridian GE bearings (paragraph 83) have been found with significant amounts of fretting between the axle and inner ring.

[18] ASM International, Metals Handbook, desk Edition, second edition, page 980.

116 It is likely that initially fretting wear, combined with inner ring growth, reduced the GE bearing interference fit in the failed gearbox to a level at which inner ring creep (paragraph 78) was initiated. This would have resulted in an acceleration of the wear rate. Inner ring creep is driven by the loading of the bearing and can be exacerbated during cold starting conditions[19]. When a gearbox is started from cold the oil viscosity is higher (ie the oil is thicker) and the heat generated within the bearing is greater. Additionally, it takes time for heat generated by the bearing to soak into the axle and, consequently, for a time the temperature of the inner ring will be higher than that of the axle. This causes the inner ring to expand off the axle, the interference fit to reduce, and creep to be exacerbated.

### *Measurements of bore growth*

117 The bore of the NGE bearing from the failed axle (which had been subject to abnormal temperatures of around 350°C), was found to be 48 μm larger than the normal maximum bore size (199.975 mm). However, because the relationship between inner ring growth and temperatures at these levels is not known, it was not possible to estimate from this measurement how much of this growth had occurred before the failure.

118 In order to assess the amount of inner ring growth that could have occurred, eight Meridian output bearings were removed from four gearboxes which had been in normal service for between 0.4 and 1.1 million miles (0.6 - 1.8 million km). These were measured, without abrasive cleaning, using a *coordinate measuring machine* (CMM) and compared with the dimensional limits for the bearing bore (199.950 to 199.975 mm[20]). The results showed that seven of the eight bearings had oversized bores (ie greater than 199.975 mm) by between 0.003 and 0.011 mm (3 – 11 μm). One bearing was still within tolerance at 199.967 mm. The average bore diameter of the eight bearings was 199.980 mm.

119 The bearing bores were re-measured after light cleaning to remove the accumulated fretting oxide. These results gave a maximum bore size of 200.000 mm (oversize of 25 μm) and an average bore diameter of 199.986 mm (oversize of 11 μm). Timken expressed the view that the inner ring bores had fretted significantly and that a significant proportion (which could not be quantified) of the resulting bore growth had been caused by fretting wear.

120 The starting bore size of these bearings is not known because they are not routinely measured when manufactured (but are checked with a *go/no-go* gauge). Taking the largest bore size measured after cleaning, the amount of bore growth could be anywhere between 25 μm (if it had started at the top end of the tolerance or 199.975 mm) and 50 μm (if it had started at the bottom end of the tolerance or 199.950 mm). Assuming the bearing started life with a bore around the middle of the tolerance band, it had grown by around 37 μm due to a combination of inner ring growth and fretting wear. This indicates that a significant amount of bore growth could have occurred on the East Langton axle.

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[19] T S Nisbet, G W Mullet, 'Rolling bearings in service, interpretation of types of bearing damage' (page 70) published by Hutchinson Benham Ltd, 1978, ISBN 0091298806.

[20] The original bore sizes of the bearings are assumed to have been in this range since each is checked with a go/no-go gauge as part of Timken's quality control process.

121 Timken undertook tests on a batch of 35 new bearing inner rings to estimate the amount of inner ring growth that could be expected due to metallurgical and temperature effects alone. The bearings, which were of a similar type to those used on the Meridians, were heated in an oven at 90°C (to simulate Meridian gearbox bearing operating temperatures) for a continuous period of 1000 hours. The maximum amount of bore growth measured was 5 μm. Timken estimated that if the duration of the tests had been longer, the amount of bore growth is likely to have reached a plateau at around 10 μm. As stated earlier (paragraph 114), bearing loading can also affect inner ring growth and these results tend to confirm that the transformation of retained austenite is only partly responsible for the bore growth process.

122 The engineering section of Timken's product catalogue[21] points out that some size change will always occur. Satisfactory dimensional stability is defined as a size change of less than 0.0001 mm (0.1 μm) per mm of bearing diameter, after exposure to temperatures of 300°F (149°C) for 2500 hours. For a 200 mm bore, growth of up to 20 μm could therefore be expected. Timken subsequently confirmed that it would expect 5 - 20 μm of bore growth in service, excluding any wear due to fretting.

*Measurement of retained austenite*

123 Tests were carried out to determine the amount of retained austenite content in one new and one used Meridian output bearing which had run for around 683,000 miles (1.1 million km). The results obtained were also corroborated by Timken. The levels of retained austenite were found to be generally in line with target levels provided by Timken before the tests.

Combined effect of inner ring growth and seat shrinkage (due to the gear fit) on the GE bearing interference fit

124 For a particular bearing application, Timken normally specifies a minimum level of interference fit, based on its practical experience and discussions with the customer. For this particular bearing, fitted to a solid shaft, Timken's standard specification for the interference fit is 76 - 123 μm[22]. This is similar to the design range of interference fit for the Meridian final drive output bearings (75 - 120 μm).

125 The level of interference below which inner ring creep is triggered for this GE bearing and its particular loading is not a standard value, and is not known precisely by Timken. Timken have advised the investigation that it would expect the value to be around 40 μm (ie below this level of interference the inner ring could start to creep on the axle). This value is consistent with the theoretical minimum interference for this bearing size and loading estimated from standard formulae[23]. Evidence of the early stages of inner ring creep was found on two Meridian bearings with interference fits of 11 and 19 μm (table 1), which suggests that the trigger level for inner ring creep for this bearing may be lower than 40 μm.

[21] http://www.timken.com/en-us/products/Documents/Engineering%20Section.pdf, page A166

[22] 'The tapered roller bearing guide', the Timken company, 2002.

[23] http://www.ntnamerica.com/pdf/2200/brgfits.pdf, section 7.

126 A statistical analysis of tolerances was undertaken using a *Monte Carlo simulation* to assess how many of the 286 operational powered axles in the Meridian fleet would be expected to start inner ring creep for various trigger levels of interference. The parameters used for this analysis and the limits between which they were randomly sampled (assuming a normal distribution of the parameters) were as follows:

- Bearing inner ring bore: 199.950 - 199.975 mm (normal tolerance).
- Bearing seat diameter on axle: 200.050 - 200.070 mm (normal tolerance).
- Bearing seat shrinkage due to gear wheel fit: 0.021 - 0.038 mm (paragraph 105).
- Inner ring growth:
  - 0.005 - 0.020 mm (expected growth without fretting wear, paragraph 122): and
  - 0.005 - 0.037 mm (expected growth with fretting wear, paragraph 120).

127 The results obtained are shown in table 2. With normal inner ring growth (ie no allowance for fretting wear), no axles would be expected to start creeping if the trigger level of interference was 20 μm or less. If the trigger levels were 30 μm and 40 μm, then around 3 axles and 26 axles respectively would be expected to suffer inner ring creep.

128 If the range of inner ring growth is extended to 5 - 37 μm to allow for fretting wear, one axle would be expected to start inner ring creep even if the trigger level was 10 μm. For trigger levels of 20 μm, 30 μm and 40 μm, 7, 35 and 94 axles respectively would be expected to suffer inner ring creep. During the investigation four Meridian axles from the operational fleet were found to have suffered inner ring creep (table 1). This fits well with the statistical prediction for an inner ring growth range of 5 - 20 μm and a trigger level of interference of around 30 μm or a trigger level of around 20 μm and the wider range of combined inner ring growth and fretting.

| | Number of axles expected to start inner ring creep for the following trigger levels of interference: | | | |
|---|---|---|---|---|
| Inner ring growth range | *≤10 μm | ≤ 20 μm | ≤ 30 μm | ≤ 40 μm |
| 5 – 20 μm | 0 | 0 | 3 | 26 |
| 5 – 37 μm | 1 | 7 | 35 | 94 |

*Table 2: Results of Monte Carlo simulation* [* '≤' represents 'less than or equal to']

129 The above analysis confirms that the existence of a population of axles which have suffered inner ring creep can be explained by a combination of normal tolerances, shrinkage of the GE bearing seat (due to the gear) and inner ring growth. These axles would then be vulnerable to further loss of interference due to wear as inner ring creep develops. The analysis does not assume that any axles in the population were manufactured with undersized GE bearing seats. This is a possibility (paragraph 107) and, had it been the case, any such axles would have progressed faster through loss of interference and into inner ring creep.

## The maintenance regime

130 **The nature and rapidity of the failure precluded prior detection by the gearbox maintenance regime at the time. It is possible this was causal.**

131 The routine maintenance regime for the final drive gearboxes on the Meridian fleet comprised four tasks:

- oil level and leakage check every 36 days;
- oil sampling every 36 days;
- oil change every 108 days; and
- final drive examination every 216 days.

Regular oil sampling is a common feature of maintenance regimes for railway gearboxes and is used to check for early signs of impending failure.

132 Oil sampling and oil changing on the failed gearbox were carried out in accordance with the required schedule from the end of 2005 onwards. The last two routine oil samples before the accident were collected on 17 February and 11 January 2010 and results were processed on 19 February and 14 January respectively. Iron from the steel used to manufacture bearings and gearbox components, is usually found in oil as components wear normally. Abnormally high iron content in the oil is one of the useful indicators of emerging problems. The last oil sample gave, amongst other data on metallic and non-metallic content within limits, an iron reading of 55 parts per million (ppm) and a *Particle Quantifier index* (PQI) of 20. The previous sample gave iron readings of 45 ppm and a PQI of 13. The corresponding operating caution limits for iron content used by Bombardier at the time were >100 ppm and >15 respectively. These limits were based on its experience on other rolling stock.

133 Bombardier's oil analysis contractor commented on these samples, that there was no cause for concern and that they would observe the next sample. The contractor had previously identified two samples with elevated PQI readings of 47 on 9 December 2009 and 90 on 27 April 2009 (corresponding ppm values of 43 and 38 respectively) and commented that the next samples should be observed to see if they were also high. The next samples showed reduced PQI levels of 15 and 13 respectively.

134 Bombardier has stated that occasionally the readings exceed the caution limits even when the gearbox is operating normally. This might occur if for example the oil sampling tube accidentally contacts the bottom of the sump or the sides of the sampling hole during the sampling process. In such cases a judgement is made, taking into account all the other data and any comments from the oil analysis contractor, as to whether the gearbox should be removed from service, a further oil sample is taken immediately, or the next scheduled oil sample (ie 36 days later) is checked before any action is decided.

135 Using oil sampling records, the cumulative iron generated during the whole service life of the failed gearbox was estimated. This is an indication of the amount of ferrous wear that had occurred and was compared with the three other axles with known clearances of around 80 µm at the GE bearing axle/inner ring interface (table 1) and which had similar service mileages, to see if there was any indication that the failed axle could have had a clearance. The results indicated that the failed axle had probably generated the highest amount of iron up to the time of failure. This was greater than found for the other axles that had a clearance, and significantly more than those which did not have a clearance. This comparison indicated that the East Langton axle probably had a loose fitting GE bearing at the time of failure.

136 The last oil change and oil sampling prior to the accident were carried out by one person and checked independently by another. Neither person saw any tell-tale signs of overheating or other distress to the gearbox. This is quite possible given the evidence obtained from the gearbox testing (paragraph 88) and thermal modelling (paragraph 73) which both indicate that the gearbox could have overheated rapidly and deteriorated from appearing normal to a failed condition in a matter of hours.

137 The oil sample data from gearboxes 1 and 2 during the laboratory tests (appendix E) showed that generally the metallic and non-metallic content detected by *spectroscopic* methods (ie the ppm values) stayed below the pre-East Langton caution limits when running with the normal oil quantity. Gearbox 1 exceeded the caution level on only one of 17 oil samples, with a value of 107 ppm. The maximum iron content recorded by gearbox 2 was 76 ppm. However, the maximum values of PQI at the start of load cycle testing of 69 and 170 for gearboxes 1 and 2 respectively were much higher than the operational limit for Meridians. Once the test gearboxes had run for a few hours, the PQ indices had settled to between 20 and 40 for both gearboxes. Therefore by comparison with the results of the last oil sample taken from E1692/07 (paragraph 132), it is quite possible that there could have been a clearance between the axle and inner ring (and wear at this interface) without necessarily registering high values in the oil samples.

138 The tests also showed that once the gearboxes had been run in, the level of wear metals generated in the oil, particularly iron, remained relatively constant until the oil quantity was reduced below 3 litres. As the oil quantity was reduced further, a rising trend was noted, which is to be expected, as the concentration would have increased even if the rate of iron generation remained constant. The PQI also did not register a rising trend until the oil quantity was reduced below 3 litres.

139 An assessment of how the oil samples from gearbox 1 varied with time after the test was stopped, showed that the iron level (ppm) and PQI reduced with time due to the effects of settling. After 4 hours, iron content was 93% of the initial value and after 10 hrs it was 75%. After the same times, PQI was 66% and 36% of the initial values. These results indicated that the time at which oil samples are taken affects the results obtained, with scope for significant variation.

140 The possibility that the last oil samples taken from the axle which failed at East Langton had been adversely affected by a delay in sampling the oil was investigated by further tests on a service train. Four gearboxes were tested by taking oil samples at two-hourly intervals over a period of 24 hours. The first sample was taken around 30 minutes after the gearboxes had stopped rotating and around 60 minutes after the train had arrived at the depot from a service run between Sheffield and Derby. The results showed that there was no significant reduction of the iron levels in both the PPM and PQI readings or of other elements over the monitoring period. Therefore there is no evidence that any significant reduction of iron levels in last two oil samples had been caused by not carrying out the oil sampling immediately the train arrived for its B exam on 14 February 2010.

141 The oil settling results from the service train differ from those obtained during the Voith test. The RAIB considers that both test results are valid. It is likely that the difference is due to a combination of two factors. Firstly, the temperature at the start of the sampling exercise in the Voith test was higher (around 80°C) than in the service train test (around 30°C). Secondly, the amount and size of wear particles in the Voith test (as seen on the dipsticks) was greater. Settling time is known to be affected by oil viscosity and particle size.

142 At the time of the East Langton accident, the train maintainer (Bombardier) did not have controls in place to specify when the oil samples should be taken after the train stopped. Generally, variation in this factor has been known to affect oil sample results, but it is unlikely that in this case tighter controls on the timing of sampling would have detected an emerging problem with axle E1692/07 for the reasons given at paragraph 140.

143 Assuming axle E1692/07 did have a loose fitting GE bearing, the only detectable signs before the accident that something was abnormal about this axle are likely to have been:

- The amount of cumulative iron generated compared to other axles, including those later found to have a clearance. To monitor this, it would have been necessary to track the cumulative iron over the whole life of the axle, which was neither the maintainer's nor the industry's common practice for oil sampling.
- The colour of the oil at the last oil sample. During the investigation it was found that the appearance of the oil (ie whether light or dark coloured) was a potentially useful tell-tale sign of a loose bearing and was used to detect the three axles with known clearances in table 1. Prior to the East Langton failure there was no specific requirement to assess the colour of oil samples taken from the final drive gearboxes.

## Identification of underlying factors[24] associated with the final drive gearbox failure

Design of the final drive gearbox

144 **The effect of the interference fit of the gear wheel on that of the GE bearing was not identified during design. This was an underlying factor.**

145 Bombardier contracted with Voith for the supply of the final drive gearboxes for the Meridian fleet, in accordance with a Bombardier specification. Bombardier has stated that this was developed from an earlier specification for Class 220 Voyager trains and included minimum axle diameters (in order to maintain axle stresses within allowable levels). Bombardier stated that the scope of supply also included the specification of detailed tolerances for the interfaces between the gearbox and the axle (ie the gear wheel, bearing and labyrinth seal seats). Voith has verified that the tolerances for these interfaces was in its scope of supply. In addition to the detailed technical specification, the contract included general requirements for the supplier to design, manufacture, test, commission and support Bombardier with best practice engineering. It also required that the supplier obtain all necessary railway approvals associated with the design of the gearbox.

146 As the train manufacturer, Bombardier had overall design responsibility for all aspects of the train. It conducted a quantified risk assessment which included consideration of the risk of an overheating gearbox resulting in an axle failure. The frequency of such an event was estimated at $1.43 \times 10^{-8}$ per train hour and assessed to be as low as reasonably practicable, on the following basis:

- the final drive was produced by a reputable transmission manufacturer with several decades of experience;
- the Voith design was, in Bombardier's belief, in accordance with best industry practice;
- similar designs had been used in 236 other 160 km/h applications and 60 other 200 km/h applications, including the Voyagers; and
- maintenance procedures would be in place to ensure that seizure of the gearbox due to lack of oil, believed to be the most likely cause of final drive failures, was minimised.

147 Bombardier has stated that its risk assessments were reviewed by a Notified Body, Network Rail's Rolling Stock Acceptance Board and an Independent Safety Assessor. These approval steps were all part of the acceptance process for new passenger rolling stock. The review processes, however, were concerned with a high level overview of hazards and ensuring that appropriate mitigation was in place. Detailed scrutiny of calculations on an item such as a final drive gearbox would be limited to checking that the component met applicable standards such as those pertaining to structural integrity. The review processes did not include checks that Voith had performed appropriate calculations on the bearing fits.

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

148 Voith has stated that it did not undertake any analysis to assess the effect of the gear interference fit on the fit of the adjacent GE bearing. There are no records that Voith asked Timken to do this. Voith's custom and practice for solid axles was carried straight through to this hollow axle design which features a relatively thin (45 mm) walled hollow axle in the area of the output bearing seats. The Voyager and Meridian axles were the thinnest walled hollow axles for which Voith had supplied a gearbox. Timken confirmed that it was not requested by Voith to undertake any analysis to assess the output bearing fits for the Meridian gearbox, and it is unclear how the final bearing seat tolerances were established between Voith and Timken.

149 Some basic analysis was undertaken by Timken for Voith for the Class 220 and 221 gearboxes which preceded the Meridian design and which also featured hollow axles. However, these were based on an early sketch provided by Voith which showed a solid axle and therefore Timken was not aware these axles were hollow. It is also unclear how the final output bearing fits were specified for the Class 220 and 221 gearboxes. Timken has stated that it did not make any formal recommendations on bearing fits, but that a sales engineer at the time may have discussed the fits verbally with Voith. There are no known records of these communications. However the fits may have been determined between Voith and Timken, the final values of interference of 75 – 120 μm are consistent with standard Timken catalogue values for this bearing (paragraph 124). Timken has explained that the bearing fits which it specifies in its catalogues apply once all other initial factors (in this case the adjacent gear fit) have been accounted for. The recommended fits are designed to allow for bore growth up to the appropriate maximum for each type of bearing (20 μm in the case of this 200 mm bore bearing).

Lack of previous similar failures

150 **There were no known previous similar failures to alert the industry about the potential for an axle failure arising from a final drive output bearing failure, and the need for mitigation of output bearing failures was not perceived. This was an underlying factor.**

151 As part of this investigation the RAIB searched for previous incidents in which failures of final drive gearbox output bearings had resulted in axle failures and derailments. Contacts were made with European safety authorities and national investigation bodies but none of those who reported back could recall any similar incidents. The companies directly involved in this accident, all of whom have considerable market experience, also could not recall any similar incident.

152 The assessment of risks arising from faults or defects in the transmission system (considered during the design process) is influenced to a large extent by previous failures and accidents. Known failure modes which have led to previous accidents (eg axle fatigue failures) inevitably form the focus of attention of designers. If a failure mode has not been seen before, it is difficult to quantify the frequency of occurrence and therefore to correctly evaluate the risk. In this case, the lack of previous failures appears to have contributed to an inadequate focus on ensuring correct final drive output bearing fits.

153 Generally, total failures of axle mounted bearings are rare and have in the past been confined to the axle bearings which support the weight of the vehicle. When failures do occur, the consequences, such as derailment, can be severe. Impending axle box bearing failures are usually detected by track mounted HABDs which are located just outboard of the running rails and measure the temperature of outboard bearing axles (which are used on the majority of UK rolling stock). The Meridians, in common with the Class 220 Voyagers, have inboard bearing axle boxes. Their temperatures cannot be detected by standard HABDs on the Network Rail infrastructure because with this design the wheel is between the bearing and heat detector. Therefore, these trains are fitted with an on-board hot axle box detection system, which automatically alerts the driver (by means of a red warning lamp and alarm in the cab) in the event that the bearing temperature rises above a pre-set value.

154 In common with all other UK rolling stock fitted with final drives, an output bearing failure detection system was not fitted to the Meridians at the time of the accident. This was because the risk from an output bearing failure was perceived to be low, there having been no precedent for such failures leading to complete axle failure. Had there been such a system, as was subsequently fitted to both Meridians and Voyagers after this accident (paragraph 197), the axle failure could have been avoided, assuming prompt action by the driver to stop the train.

*Service experience on Voyager trains*

155 There have not been any similar total failures of final drive gearboxes or axles on the Voyager fleet, which share the same gearbox design and have very similar hollow axles. There has been only one case of a Voyager GE bearing which showed signs of inner ring creep, but four cases on Meridians where clearances have developed (table 1). This indicates that the Voyagers are not as prone to this problem as the Meridians. The single case of inner ring creep on a Voyager GE bearing was found after it was removed on 14 October 2008 due to high iron content in the oil sample. It had run 250,000 miles (402,000 km) since its last overhaul and 1.55 million miles (2.5 million km) since it first entered service. The bearing seat on the axle was similar in appearance to those discussed at paragraph 83 but further information is not available.

156 The investigation considered whether there was any relevant evidence from the higher frequency of output bearings suffering inner ring creep on Meridians relative to Voyagers, which could shed light on the cause of the failure mode at East Langton. There are some possible factors which, acting either separately or in combination, could have led to the observed differences, such as:

- differences in duty cycle and operating temperature (which could affect inner ring growth and fretting wear);
- differences in wheel damage and the resulting forces on the gearbox and axle (which could affect inner ring growth and fretting wear); and
- changes to, or variations in, the manufacturing processes of the axle and bearing components (which could affect bearing metallurgy and axle size).

An assessment of relevant differences between these two types of stock and their possible effect on the bearings and axles is beyond the scope of this investigation. However, it is the subject of ongoing analysis by the vehicle manufacturer (paragraph 195). At the time of reporting, no conclusions had emerged from this work that could explain the observed differences.

## Factors relating to the operation of the train during the accident

157 The consequences of the derailment could have been worse if, for instance, the derailed wheelset had encountered a set of *points* and deviated significantly from the down line. It took 118 seconds and a distance of 2.2 miles (3.5 km) to stop the train from the first appearance of the red bogie fault lamp (paragraph 37). Had a full service brake been applied immediately, that distance would have been around 0.6 miles (1 km). The factors which led to an increased risk to passengers and damage to the track and train were:

- the driver's delayed reaction to the red bogie fault alarm in the cab; and
- the decision to stop the train beyond a cutting, rather than before it, which introduced further delay.

These factors are discussed in the following paragraphs. Appendix F contains details of the relevant alarms triggered during the derailment, the information provided to the driver, and the actions required of the driver.

### The driver's initial reaction to the red bogie fault alarm

158 **There was an initial delay before the driver began to reduce the train speed after receiving the red bogie fault lamp and audible alarm. This was a contributory factor.**

159 The delay in reacting to the red bogie fault alarm in the cab occurred for the following reasons:

- The driver did not follow the correct procedure in the event of a red bogie fault alarm. This is discussed further at paragraph 166.
- The driver stated that he was unsure if the red bogie fault alarm was real or spurious, because he was aware of problems on Meridians in the recent past with spurious alarms for hot axle boxes. Spurious alarms are discussed further at paragraph 160.
- The driver was located three coach lengths forward of the derailed vehicle and states that initially there was no indication, from the response of the train, of a serious problem. Even after he felt the train behaving abnormally he did not think it was derailed.

### *Previous spurious alarms*

160 During a four-week period from mid-December 2009 to mid-January 2010 the Meridian fleet experienced 15 activations of the yellow TMS level 3 alarm with the TMS anomaly window (appendix F) indicating a hot axle box. However, the red bogie fault lamp had not illuminated on any of these occasions. In two cases the alarm was found to have been caused by faults not related to hot axle boxes, and in the remaining 13 cases the activations were spurious with no faults being found.

161 These spurious activations were all attributed to heavy snowfall at the time, which had caused water ingress into the hot axle box detection equipment, falsely triggering the yellow TMS level 3 alarm, but leaving the red bogie fault alarm unaffected. The detection system for a hot axle box is operated by a compressed air supply. If an axle box overheats, a fusible plug melts and releases air pressure. The pressure drop is detected by a pressure switch which contains two sets of contacts; one controls the red bogie fault lamp and the other controls the (yellow) TMS level 3 fault lamp. When the train is in operation, the set of contacts for the red bogie fault lamp are closed and the other set for the TMS level 3 lamp are open. In extreme wet weather, water can penetrate the pressure switch and make an electric current path between the open contacts for the yellow TMS level 3 lamp, causing it to light up. There is no effect on the closed contacts for the red bogie fault lamp.

162 The spurious alarms were causing drivers to stop their trains and investigate the fault and this was causing disruption to services and operational difficulties for East Midlands Trains. There was discussion within the company about the necessity for drivers to stop in these circumstances. Operations staff did not want to ignore a yellow (non-safety critical) alarm if no red bogie fault lamp was illuminated, because the fault displayed on the TMS anomaly window (hot axle box) is a safety critical condition.

163 The outcome of the discussions within East Midlands Trains was the issue of an Operating Notice 'Spurious HABD activations and management of level 3 alarms'. This gave interim advice on the action to be taken in the event of a (yellow) TMS level 3 alarm being received in relation to a hot axle box detector activation on the Meridians. This notice was issued on 5 January 2010 and posted in the new notice cases at the booking-on points for drivers at Derby and St Pancras for three weeks and then transferred to the general notice cases for five weeks. It was on display in the general notice case at the time of the East Langton accident. Drivers are required to read notices posted in these notice cases. The operating notice set out the following procedure in the event of any level 3 alarm being received in the cab:

- acknowledge the level 3 warning alarm;
- bring the train to an immediate stand at the first safe and suitable location;
- interrogate the TMS to identify the defect present;
- contact the signaller to advise of the situation;
- contact (Bombardier) maintenance control to report the activation and details of the event;
- if the TMS advises of an HABD activation, check the 'Bogie Fault' light;
- if the 'Bogie Fault' light is not lit, then acknowledge the defect on the TMS and advise the signaller that the train can continue normally ;and
- if a further TMS HABD related level 3 alarm sounds <u>with or without</u> a 'Bogie fault' light being present, then the HABD should be considered defective and the appropriate measures undertaken for reporting, examination and isolation.

164 The procedure in the Operating Notice was East Midlands Trains' policy on alarm handling at the time of the East Langton accident. East Midlands Trains expected that drivers would read the notice as they are required to do, but it had not been actively briefed out to them. The driver of 1F45 was aware of the notice but could not recall the detail.

165 The driver of 1F45 had never experienced a spurious (yellow) TMS level 3 alarm but was aware that these had been occurring from mess room discussion. Although there are no known cases of other drivers failing to stop for spurious alarms, it is possible that the driver's knowledge of the spurious alarms had put doubt in his mind as to whether the red bogie fault alarm received at East Langton was genuine. This may have contributed to the delayed response.

*Alarm handling procedures and training*

166 Initially, on receiving the red bogie fault lamp and associated audible alarm, the driver did not start to brake his train but instead became busy interrogating the TMS to try and find out more about the fault causing the alarm. This was contrary to procedures and resulted in a delay of 23 seconds from receiving the red bogie fault lamp to making the first brake application. Interrogation of the TMS appears to have led to a temporary loss of awareness of the train's location such that on returning his attention back to the track, the driver thought he was closer to the cutting than he actually was.

167 The Operator's Manual issued by Midland Mainline Limited (the predecessor to East Midlands Trains) when the Class 222 Meridian was first introduced and on which the driver was trained, sets out the responses required by the driver to fault alarms (appendix F, table F2). On the illumination of a red fault lamp, the driver is instructed 'to stop the train at the first suitable location' and report the circumstances to the signaller. The instructions go on to state that once stopped, the driver is to consult the TMS for further information on the cause of the fault lamp. If a yellow level 3 TMS lamp is illuminated and no red lamp is lit, the driver is instructed to continue until the next station and carry out the same procedure.

168 The phrase '….at the first suitable location' used in the Operator's Manual is derived from Railway Group Standard GE/RT8000 (the Rule Book), Module M1, Section 5, 'Fire on a train'. This broadly states that, in the event of a fire, the train should be stopped immediately, but where possible not in a tunnel, on a viaduct, or at any other unsuitable place where it would be difficult to tackle the fire or dangerous for any necessary evacuation of passengers. There is a similar reference to stopping a train in a suitable location in the rules for drivers responding to a PCA activation (module TW1 of the Rule Book, 'Preparation and movement of trains – General'), unless the driver believes the train is in danger, in which case they should stop the train immediately.

169 Training material used by East Midlands Trains included an interactive 'virtual train' DVD developed to teach drivers about alarm handling. It paraphrases the wording of the Operator's Manual and the Rule Book and instructs drivers that on receipt of a red fault lamp they should bring the train to an immediate stand (or promptly bring the train to a stand) at the first safe and suitable place. In such circumstances, all the training material states that the TMS should only be consulted for information on the source of the fault once the train is at a stand.

170 East Midlands Trains' drivers are tested on their theoretical knowledge of the procedures during routine competence assessments; however the company does not use any form of simulation during training and assessment. Therefore drivers are not systematically tested in the various out-of-course scenarios they may encounter in service and are not able to practise the required responses. The correct and timely response to out-of-course situations has been the subject of a previous RAIB investigation and recommendation, discussed later at paragraph 203.

*Knowledge of procedures*

171 On completion of his training on the Meridian in October 2008, the driver was questioned in the final test about the action to take in the event of a red bogie fault lamp. He answered correctly, stating that a driver should stop his train immediately at a suitable location.

172 In August 2009 the driver attended an East Midlands Trains safety training update briefing during which there was a showing of a training DVD 'Class 222 Fault Finder' and an assessment, both of which related to alarm handling. The DVD included the procedure to be followed by the driver in the event of a red bogie fault lamp. As part of the assessment the driver completed a 'Class 222 underpinning knowledge questionnaire' which also demonstrated his awareness of the meaning of a red bogie fault lamp. He correctly identified that a red bogie fault lamp would be lit for a hot axle box, cardan shaft or air suspension fault.

173 However, by the time of the accident at East Langton, the driver had come to believe that the procedure for alarm handling was that on receipt of a red bogie fault lamp, he should first interrogate the TMS for further information on the source of the fault, so that a decision could be made on the appropriate response. Accordingly, when he received the first red bogie fault lamp, he touched the screen to activate it (the TMS touch screen is normally blank until activated by the driver). The driver reported that in the 16 months he had been driving Meridians, he had not experienced a red fault lamp before, but had dealt with three or four PCA applications by passengers.

174 The driver also understood the instruction to bring the train to an 'immediate stand at the first safe and suitable location' (paragraph 169) to mean that he was to find what in his judgement was a suitable place, and then stop. He did not interpret the instruction to mean he should give immediate priority to stopping the train over finding a suitable place to stop.

The decision to stop the train beyond the approaching cutting

175 **The driver decided to stop the train beyond a cutting which he considered to be an unsuitable place to stop. This caused further delay to stopping the train and was therefore a contributory factor.**

176 By the time the driver decided he would have to stop the train, it was approaching a cutting. The driver stated that in his judgement and according to his recollection of the rule book (which applies to fire), a cutting, like a tunnel or viaduct, was not a suitable place to stop a train. He was also aware that there was road access beyond the cutting which would facilitate evacuation of passengers and so he re-applied power (paragraph 39) approximately 39 seconds after the red bogie fault lamp appeared and 12 seconds before the fire alarm sounded.

177 Once the fire alarm sounded, it became the focus of the driver's attention and he maintained his plan to get the train through the cutting. He continued applying traction power for approximately four seconds after the fire alarm sounded and then, realising that the train was not responding, coasted for a further 11 seconds before finally re-applying the brake. By this time the train was oscillating badly and the driver knew that something was seriously wrong. Had he applied full service brake when the fire alarm sounded (approximately 1.2 km from the start of the cutting), the train, which was travelling at 75 mph (121 km/h) at the time, would have been able to stop around 0.5 km before the cutting.

178 When the PCA was activated by a passenger (21 seconds after the fire alarm), the driver overrode it in order to get through the cutting. He did not establish communication with the passenger who had operated the PCA; however, as drivers are trained to prioritise the safe stopping of the train over speaking to the PCA operator, this is not abnormal.

179 The Rule Book Module M1, section 5.1, does not specifically state that a cutting is an unsuitable place to stop a train in the event of a fire. The East Midlands Trains' Professional Train Driving Policy in force at the time of the accident did not define what was, or was not, a suitable place to stop a train. The version of the document published in May 2010 in relation to fire on trains, suggests that a cutting may be an unsuitable place to stop. Given that the driver became focused on the fire alarm and was not aware that the train was running derailed, his interpretation is not inconsistent with either the Rule Book or East Midlands Trains' driving policy.

180 When the driver realised from the abnormal way the train was handling during the latter stages of the derailment, that he was not going to be able to drive the train through the cutting, he applied around 50% braking instead of emergency or full service brake. He stated that he did not want to brake any harder in case the rapid deceleration caused passenger injuries.

## Identification of underlying factors associated with the operation of the train during the accident

181 **Refresher training on alarm handling provided to drivers and on-board train crew, following the incident at Desborough in June 2006, did not adequately cover handling safety critical alarms and out-of-course situations. This was an underlying factor.**

<u>Previous incident involving similar train crew response</u>

182 On 10 June 2006 there was an incident on the Midland Main Line near Desborough (RAIB Report 31/2007 and paragraph 203), in which a door on a Class 222 Meridian came open in traffic. This caused an automatic brake application and a fault lamp to be lit in the driver's cab. The driver interrogated the TMS for further information but, due to the particular nature of the fault, no anomalies were listed. The driver, on being unable to establish the cause of the brake application decided to depress the brake override switch, which operates for 30 seconds before timing out and automatic braking is resumed. The driver applied the override switch three times so that he could get his train to the next *signal post telephone*, from where he could contact the signaller. The train had travelled for approximately five minutes with the door open.

Driver and crew training in out-of-course or emergency situations

183 The incidents at Desborough and East Langton have the following similarities:

- the drivers' responses to the alarms were to interrogate the TMS for further information while driving, contrary to company procedures, because they were hesitant about treating the alarms as genuine;
- when they realised the alarms were genuine, the drivers were more focused on a 'suitable place to stop' than on stopping their trains immediately, thereby increasing risk to passengers in both cases; and
- the customer hosts, who were aware of the emergency situations, either did not or could not successfully operate the PCA, which additionally applies the emergency brake.

184 Following the incident at Desborough, Midland Mainline and later East Midlands Trains developed training material and undertook briefing sessions for all drivers and train crew (paragraph 204). However, the similarity of the driver and customer host responses at Desborough and East Langton indicates that the scope and depth of the training given was not sufficient to elicit the correct response at East Langton.

## Previous gearbox incidents of a similar character

185 As explained at paragraph 150, there have not been any previous derailments initiated by failure of a final drive output bearing. However, there have been two previous incidents in which final drive gearboxes have overheated but which have not resulted in total failure of the axles.

186 In 2005 a Meridian final drive gearbox was inspected by Voith and found to have a spinning GE bearing inner ring. No formal inspection was carried out but the failure was attributed to a lack of oil in the gearbox.

187 In 2006, a shunter at Derby Etches Park Depot detected a hot final drive gearbox on Meridian set 222010 which had caused the axle to seize. The gearbox had run approximately 1500 miles since its last exam. Voith inspected the gearbox and attributed the failure to a lack of oil. Bombardier subsequently introduced independent checks at oil change.

# Summary of Conclusions

## Immediate cause

188 The immediate cause of the derailment was the overheating and subsequent fracture of the powered trailing axle of the leading bogie of the fourth vehicle in the train.

## Causal factors

189 As explained at paragraph 95, these conclusions have been derived from an assessment of the available evidence in order to identify the factors which, in the view of the RAIB, were most likely to have combined to cause the fracture of the axle. These factors are as follows:

a) spinning of the axle within the inner ring of the GE bearing, due to rotational stiffening of the bearing, which was causal (**paragraph 97, Recommendations 1 and 2**);

b) insufficiency of the interference fit of the GE bearing inner ring onto the axle at manufacture, due to the effect of the adjacent gear wheel fit on the hollow axle, which was probably causal (**paragraph 102, Recommendations 1 and 2**);

c) the bearing seat on the axle may have been manufactured undersize, which was possibly causal (**paragraph 107, Recommendation 2**);

d) progressive loss of the GE bearing interference fit in service, due to bearing bore growth and fretting wear, which was probably causal (**paragraph 112, Recommendation 2**); and

e) the nature and rapidity of the failure precluded prior detection by the gearbox maintenance regime at the time, which was possibly causal (**paragraph 130, Recommendation 3**).

## Contributory factors

190 Factors which exacerbated the consequence of the derailment in terms of delayed stopping of the train and therefore increased risk to passengers and caused greater damage to the track and train, were:

- the initial delay before the driver began to reduce the train speed, after receiving the red bogie fault lamp alarm (**paragraph 158, Recommendation 4**); and
- the driver deciding that he should stop the train beyond the approaching cutting which he considered an unsuitable place to stop (**paragraph 175, Recommendation 4**).

## Underlying factors

191 The underlying factors related to the failure of the final drive gearbox were:

a) the effect of the interference fit of the gear wheel on that of the GE output bearing was not identified during design (**paragraph 144, Recommendation 1**); and

b) there were no known previous similar failures to alert industry to the potential for axle failure arising from a final drive output bearing failure and the need for mitigation of output bearing failures was not perceived (**paragraph 150, no recommendation**).

An underlying factor related to the consequences of the derailment was:

c) the refresher training on alarm handling provided to drivers and on-board train crew, following the incident at Desborough in June 2006, did not adequately cover handling safety critical alarms and out-of-course situations (**paragraph 181, Recommendation 4**).

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

## National Incident Reports

192 East Midlands Trains initially issued a *National Incident Report* (NIR) 2571 on 21 February 2010 to alert the industry to the final drive failure and derailment at East Langton. Three further updates followed, the last on 28 June 2010, to update the industry on the measures that were being taken at that time, as detailed below at paragraphs 193 and 197.

## Engineering precautions

193 Following the accident, East Midlands Trains and Bombardier put in place the following measures to minimise the risk of recurrence while investigations proceeded:

- Inspections of all Meridian final drives to check that they were correctly filled with oil, in case the failure had been caused by a lack of oil.
- Torque checks on all Meridian output bearing housing bolts in case the failure had been caused by these bolts working loose (some loose and missing bolts were found on the failed final drive).
- Temperature monitoring of all Meridian, Voyager and Super Voyager gearboxes, using infra red thermometers, once trains had stopped at various allocated termini. For the Meridian fleet these were London St Pancras Station, Sheffield Station and Derby Etches Park Depot, where monitoring was continued until 15 September 2010.
- A reduction in the ultrasonic axle testing intervals for the Meridian, Voyager and Super Voyager fleets from 300,000 miles to 100,000 miles until 18 May 2010, when the original interval was restored. This was in case the failure had been caused by metal fatigue of the axle.
- Introduction of a minimum diameter of 200.030 mm for the output bearing seat on the axle, with the adjacent gear fitted. Axles found to be below this size were scrapped.

## RAIB Urgent Safety Advice

194 On 14 July 2010, the RAIB issued an urgent safety advice (USA) to the industry, including those who do not receive GB Railway Group NIRs. The purpose of the USA was to raise awareness among other operators about the accident and the emerging focus of the technical investigation. It was subsequently sent to the European Rail Agency (ERA). The USA advised that on the basis of emerging evidence, relevant considerations for designers, operators and maintainers should include:

- allowing for shrinkage of bearing seats due to other nearby interference fits (eg gear wheels, and other bearings) in the design process;
- checking that the level of interference between bearings and their shafts or housings is within the specified tolerances at new build; and
- checking bearing seats when gearboxes are overhauled, to ensure that they remain within tolerance, and assessing the extent of any growth on the bearing inner rings that are removed.

## Gearbox design review work

195 Bombardier is conducting a review of the Meridian final drive gearbox, and undertaking tests and analyses to identify any relevant differences from the performance of Voyager final drive gearboxes, in order to inform this review. Work is underway to redesign the axle to compensate for the loss of interference on the GE bearing due to the fit of the adjacent gear wheel. This work should address the underlying factor identified in paragraph 191a when it is completed and any appropriate actions are followed through. This is addressed in Recommendation 1.

## Review of passenger evacuation

196 After the accident, East Midlands Trains undertook a review of its emergency response arrangements and in particular the causes of the delay in providing a rescue train to the site and evacuation of passengers from train 1F45. Learning points were identified and East Midlands Trains has reported to the RAIB that as a result of the review, it has put in place the following measures:

- improvements to the command and control arrangements for emergency situations;
- better communication facilities so that a greater volume of telephone calls can be handled in emergency situations;
- increased frequency of exercises to practise control of emergency situations and further training of controllers;
- training of more drivers on diversionary routes to increase operational flexibility when main routes are blocked; and
- improved systems for communication with passengers at stations.

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

## Installation of output bearing over-temperature detection

197 During June 2010, Bombardier designed and began installation of the following two devices on each GE and NGE final drive output bearing on the Meridian and Voyager fleets:

- A fusible plug connected to the existing HABD system, in order to detect and alert the driver in the event of an overheated final drive output bearing. The fusible plug is set to trigger at 145°C and activate the red bogie fault lamp and audible alarm in the cab.
- A 'ribbon bolt' which activates at 125°C and indicates (by means of a tell-tale) to drivers or maintenance staff inspecting an affected bogie from the track side or in the depot, that the final drive output bearing has an overheating problem and requires immediate attention. The ribbon bolt enables the person inspecting the train to differentiate between a hot final drive output bearing and a hot axle box bearing.

198 The installations on the operational fleet were completed by 15 September 2010. Operational constraints on the laboratory test rig at Voith precluded a full test of the fusible plug in January 2011 (appendix E) and therefore Bombardier is additionally undertaking thermal modelling to check that the plug will provide adequate warning under all anticipated bearing failure scenarios. These actions, which are being monitored by the Office of Rail Regulation (ORR), the safety authority, address the need for on-board mitigation devices identified in paragraph 191b, and therefore the RAIB has decided not to issue a further specific recommendation relating to this.

## Design selection of bearing fits

199 Voith has stated that as a result of a bearing interference fit issue on another gearbox design, it has revised the design process for bearing fits on final drive gearboxes. Bearing fits are now specified by the bearing supplier. This change was effected after the design of the Voyager/Meridian gearbox (paragraphs 148 and 149) but prior to the East Langton accident. Therefore the RAIB has decided not to issue a recommendation for Voith to review its design procedures for output bearing interference fits.

## Train crew briefing

200 East Midlands Trains carried out a review of the operating instructions provided to drivers in relation to actions following receipt of a yellow level 3 alarm and red bogie fault lamp, including discussion with other train operators. The original instruction in the operating manual, to stop the train at the first suitable location, was recognised as not prohibiting the driver from proceeding to the suitable location at high speed. Consequently, East Midlands Trains clarified the instruction to read as follows:

*'In the event of a bogie fault light illuminating, an audible level 3 alarm will activate. On receiving this warning, the driver must bring the train to a stand immediately. If the location at which the train would come to a stand is not considered to be safe and suitable (as defined within the Rule Book), then the driver must reduce speed to no more than <u>10 mph</u> in order to bring the train to a halt at the first safe and suitable location that does meet this criteria.'*

201 This revised instruction was posted for the attention of drivers on 21 May 2010 together with operating procedures concerned with the newly fitted 'ribbon bolts' and fusible plugs (paragraph 197). East Midlands Trains report that its driver managers have used safety training updates to discuss the learning points arising from the accident at East Langton. Formal (signed for) re-briefing and knowledge testing of the actions to take following receipt of a red fault lamp, etc was completed on 4 October 2010.

202 In the light of these actions, which relate to the underlying factor identified in paragraph 191c, the RAIB has decided not to issue a further recommendation to re-brief train crew. However, a recommendation is made relating to practising how to handle out-of-course incidents including the handling of on-board alarms.

# Previous recommendations relevant to this investigation

203 The following recommendation was made by the RAIB as a result of a previous investigation:

*Passenger door open on a moving train near Desborough, 10 June 2006, RAIB report 31/2007, published August 2007*

*Recommendation 7*

*'Operators of class 222 trains should review the content of training courses and the assessment of drivers, train managers and customer hosts in the practical application of procedures relating to unexpected incidents that may occur while trains are running in service. This should include ensuring that on-board staff members have an adequate understanding of their roles and responsibilities, particularly with regard to the use of the emergency brake override (and where the train should be brought to a stand), the operation of the passenger communication alarm system, and the use of the TMS and other sources of fault and event indication'.*

## Actions taken by Midland Mainline/East Midlands Trains since the Desborough incident

204 In December 2008, East Midlands Trains commissioned a 'Fault Finder' DVD to update its training material on fault handling procedures, to be used in core and refresher training for drivers and on-train crew. The instruction given for an illuminated red bogie fault lamp (which is always accompanied by a yellow TMS level 3 fault lamp and audible alarm) or a PCA activation is that the driver should bring the train to an immediate stand at the first safe and suitable location.

205 The DVD was issued in March 2009 and was rolled out as part of core driver training and used in safety training update briefings for all drivers between June and September 2009. The driver of train 1F45 had refresher training in August 2009, which included a viewing of the DVD and a brief written assessment of the alarm handling procedure.

206 The RAIB's recommendation 7 from the Desborough incident was closed by the ORR on 18 September 2009. Midland Mainline, the operators of the route at that time, had reported to the ORR that it had reviewed the training of its drivers and on-board staff and where necessary, had put in place practical awareness of the PCA device as fitted to its fleet of HSTs and Class 222. It additionally put in place instructions for the length of time that drivers should override the PCA device fitted to the Class 222. The ORR judged Midland Mainline's response to be sufficient.

207 A new recommendation is made from this investigation because the focus of Midland Mainline's response to the previous recommendation was limited to handling of PCA alarms. The main issue regarding the consequences of the derailment at East Langton was response to other safety critical alarms.

# Recommendations

208 The following recommendations are made[25]:

1. *The purpose of this recommendation is to reduce the risk of recurrence of a similar final drive gearbox failure on the Meridian and similar fleets.*

   Bombardier Transportation, in conjunction with Voith, should undertake a design review of the final drive gearboxes and axles used on the Meridian and Voyager fleets (Class 220, 221 and 222) and, where appropriate, implement design and maintenance improvements, including verification of the over-temperature detection, to reduce the risk from loss of output bearing interference fits on the axles (paragraphs 189, 191a).

2. *The purpose of this recommendation is that safety lessons from the East Langton investigation, in particular that a final drive output bearing failure can lead to axle failure, are captured in procedures for the design and assembly of final drive gearboxes at new build and overhaul, to maintain adequate bearing interference fits.*

   ROSCOs and other Contracting Entities (purchasers of rolling stock), and Entities in Charge of Maintenance (responsible for overhaul of rolling stock) should review, and where appropriate improve, the design, manufacture and overhaul procedures used for final drive gearboxes in their current and future fleets, in particular those featuring hollow axles, by checking that they adequately address the following factors:

   - reduction in the size of output bearing seats due to shrinkage arising from other nearby interference fits and/or wear during service;
   - bearing bore growth during the service life of the bearing (eg obtained by measuring a sample of bearings);
   - bearing seats being made undersize; and
   - detection of overheating output bearings.

   (paragraph 189).

   **__Note for information relating to Recommendation 2__:** In conjunction with the publication of this report, the RAIB has written to the European Rail Agency (ERA) to request their assistance with the dissemination of the identified issues to national safety authorities and national investigation bodies in other member states of the European Union, for their information and action as appropriate to their circumstances.

*continued*

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25 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 purpose of this recommendation is to improve the failure detection capability of oil sampling regimes for final drive gearboxes to reduce the risk of future axle failure.*

   Bombardier Transportation should review the final drive oil sampling regime on the Meridian and similar fleets (including consideration of sampling frequency and consistency, action levels, oil colour and use of cumulative trending) and, where necessary, make changes to maximise effectiveness in detecting impending failures (paragraph 189e).

4. *The purpose of this recommendation is that train crew are familiar with, and practised in, on-board alarm handling procedures so that correct and timely action is taken to minimise adverse consequences of an out-of-course incident.*

   East Midlands Trains should provide practical, rolling stock specific, initial and refresher training, that includes the simulation of on-board emergency and out-of-course situations. This should enable drivers and train crew to maintain their understanding of, and familiarity with, correct alarm handling in various scenarios (paragraphs 190 and 191c).

**Note: Recommendations 3 and 4 may also apply to other organisations.**

# Appendices

## Appendix A - Glossary of abbreviations and acronyms

| | |
|---|---|
| AWS | Automatic Warning System |
| DEMU | Diesel Electric Multiple Unit |
| HABD | Hot Axle Box Detector |
| ORR | Office of Rail Regulation |
| OTDR | On Train Data Recorder |
| NIR | National Incident Report |
| PCA | Passenger Communication Apparatus |
| ppm | parts per million |
| PQI | Particle Quantifier Index |

## 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.

| | |
|---|---|
| Automatic warning system | A safety system for alerting drivers about the signal aspect or speed restriction ahead, sounding a horn in the cab for a red, single or double yellow aspect or a bell to indicate a green signal. It includes track mounted magnets located in the four-foot and is usually protected by a heavy steel ramp. |
| Bogie | A metal frame equipped with two or three wheelsets and able to rotate freely in plan, used in pairs under rail vehicles to improve ride quality and better distribute forces to the track.* |
| Bogie frame | The metal frame structure of a bogie which supports the vehicle body and wheelsets. |
| 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 the Meridian, between a body mounted traction motor and a final drive gearbox on the axle. |
| Cess | The part of the track bed outside the ballast shoulder that is deliberately maintained lower than the sleeper bottom to aid drainage, provide a path and sometimes (but not always) a position of safety.* |
| Chain(s) | A unit of length, being 66 feet or 22 yards (approximately 20.117 metres). There are 80 chains in one standard mile.* |
| Coordinate measuring machine | A machine for accurately measuring the geometry of a component or object. |
| Customer host | A member of the on-board railway staff whose principal duties are the serving of refreshments to passengers. |
| Diesel electric multiple unit | A self-contained diesel-powered train where the diesel engines are located beneath each vehicle and the transmission system between the engines and the wheels is electric. |
| Down (line) | Northbound, away from London St Pancras, the direction the train was running. |
| Final drive gearbox | A final drive gearbox is mounted on each powered axle and transmits the drive from the traction motor, through an angle of 90 degrees, into the axle. |
| Flange climb | A situation where the flange of a rail wheel rides up the inside (gauge) face of the rail head while rotating. If the wheel flange reaches the top of the rail head, the wheelset is no longer laterally constrained and this usually leads to derailment. |
| Four-foot | The area between the two running rails of a standard gauge railway.* |

| | |
|---|---|
| Fretting | A wear process which occurs at the interface between two surfaces in loaded contact, which also have small relative movements between them, such as those due to vibration or bending. The process causes mechanical wear at the interface and oxidation of the metallic debris. |
| Functional specification | A functional specification sets out what the equipment is required to do (including any requirement to interface with other components or equipment), rather than setting out the details of the design, which is left to the supplier of the equipment to decide upon. |
| Go/no-go gauge | An inspection tool used to check whether a component is within tolerance by a physical comparison with the gauge rather than by measurement. |
| Hollow axle | A hollow axle has a hole through the middle, like a thick tube and is different to other railway axles which are solid. |
| Hot axle box detector (track-mounted) | A device comprising axle counters, processing equipment and infra-red detectors mounted close to the rails, which monitors passing trains and alerts the controlling signal box if it senses an overheating or hot axle box. If a train activates a detector, it is brought safely to a stand for examination or remedial action.* |
| Inboard axle bearings | On Meridians and Voyagers, the vehicle's weight is supported by the axle bearings within axle boxes located inboard of the wheels. The other type of arrangement is with the axle boxes located outboard of the wheels. |
| Inner ring creep | A slow circumferential rotation of a bearing inner ring relative to the axle or shaft on which it is fitted, caused by an insufficient interference fit. It results in wear at the axle/ring interface, leading to further reduction in interference fit or even a clearance. |
| Interference fit | A fit between the axle and bearing inner ring where the bore of the inner ring is slightly smaller than the axle diameter. When fitted together the ring is tight on the axle and not free to rotate. The greater the difference in diameters, the greater is the level of interference and tightness. |
| Monte Carlo Simulation | A computerised mathematical technique used to study the effect of various parameters known to affect an outcome (in this case the interference fit of a bearing). Each parameter which affects the outcome is randomly sampled between specified limits to form a set of inputs which are used to calculate an outcome. This process is repeated as many times as required to study what might happen within a population, in this case a fleet of axles. |
| National incident report | A reporting system in the UK to initiate, disseminate and manage urgent safety related defects in rail vehicles, plant and machinery.* |

| | |
|---|---|
| Notified body | An organisation with the delegated responsibility to audit the correct application of national standards under Technical Specifications for Interoperability regulations for railways.* |
| 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. |
| Office of Rail Regulation | The economic and safety regulator for the railway industry in Great Britain. |
| ORBITA | A fleet management system which remotely downloads data from the train's TMS system for maintenance use. |
| Particle quantifier index (PQI) | A quantitative dimensionless measure of the mass of ferrous debris within an oil sample, using magnetic sensing. The index is often used in conjunction with other techniques (eg traditional spectroscopic methods) which may not be sensitive to the presence of larger particles sizes (> 5 μm). |
| Passenger communication apparatus | On-train system provided to enable passengers to communicate with the driver in the event on an emergency, and which automatically applies the train's emergency brake. The brake application can be overridden by the driver to prevent the train stopping in an unsuitable location. |
| Plastic strain | Permanent (non-recoverable) elongation which occurs to a material when it is stressed beyond its elastic limit. |
| Points | An assembly of two movable rails, the switch rails, and two fixed rails, the stock rails. Also known as a set of switches. Used to divert a train from one track to another. |
| Preloaded condition | 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. |
| Primary traction rod | Two of these rods provide a longitudinal connection between each Meridian wheelset and the bogie frame and provide the main load path for traction and braking loads between them. |
| Raceway (of a bearing) | The polished part of the bearing inner and outer rings on which the rollers run. |
| 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.* |

| | |
|---|---|
| Spectroscopic (oil analysis method) | A standard method of oil analysis using a spectrometer to measure the types and quantities of metals in an oil sample. It detects small particles of metal (<5 μm). |
| Traction motor | The electric motor used as the means of turning the powered axles on a rail vehicle using electric traction or diesel electric traction.* |
| Train Management System (TMS) | On-train computer system which monitors and records faults and other system event conditions associated with the train's electrical and electronic systems. |
| Up (line) | Southbound, towards London St Pancras. |
| Wheel impact load detector | A rail mounted strain gauge and axle counter system which records the load produced by each rail wheel. Excessively high values can indicate overloaded vehicles or wheel flats. Any such wheel detected, normally results in the train being stopped for inspection.* |
| Wheelset | Two rail wheels mounted on their joining axle.* |

## Appendix C - Key standards current at the time

| | |
|---|---|
| Railway Group Standard GE/RT8000-M1, Issue 1, June 2003. | Train stopped by train accident, fire or accidental division. |
| Railway Group Standard GE/RT8000/TWI, Issue 8, October 2008. | Preparation and movement of trains: General |

## Appendix D - Failure modes that were discounted or considered unlikely

D1 This appendix discusses the following failure modes considered during the investigation and the reasons they were discounted or considered unlikely:

- fatigue failure of the axle leading to its fracture;
- seizure of the gears leading to axle fracture;
- failure of the GE bearing causing it to become stiff in rotation or seize, leading to spinning of the axle within the inner ring, overheating and fracture of the axle, due to the following:
  - a defect or damage in the components of the bearing;
  - contamination of the bearing with internal debris such as accumulated wear particles.
  - incorrect assembly at original manufacture;
- *primary traction rod* failure;
- loose bearing housing bolts; and
- failure of the GE bearing due to a lack of oil, arising from a maintenance error or loss of oil due to puncture of the gearbox prior to the derailment.

Fatigue failure of the axle (discounted)

D2 The possibility that a fatigue failure of the axle occurred first and led to the observed overheating and damage to the final drive gearbox was examined and discounted for the reasons explained in the following paragraphs.

D3 There was no evidence on the fracture surfaces of the axle that a fatigue crack had propagated through the depth of the tube (figure D1). The whole circumference of both fracture faces exhibited a consistent tearing/shearing type failure. Had a fatigue crack propagated part way through the axle before a final overload fracture, at least some significant part of the circumferences of each half would have looked flatter and more battered.

D4 There was a circumferential bulge in the axle bore and a circumferential area of necking (thinning) of the bore adjacent to both fracture faces (figure 9a). This deformation was consistent around the whole circumference. Had there been a fatigue crack through part of the axle, this deformation would not have been uniform across the area of the fracture face.

D5 The total length of the axle (axle end faces to fracture extremities) was 26 mm longer than it had been originally. This was caused by ductile elongation of the axle and indicates that the axle had been overheated prior to the fracture. Had a fatigue crack caused the axle to fracture, the total length would have been similar to the original length or been shorter due to battering and wear between the faces.


*Figure D1: Axle fracture face*

D6 The evidence from the GE bearing did not support an axle fracture due to fatigue. The position of the fracture was within the bearing seat and offset towards the outboard edge. Had the axle fractured due to fatigue, the two halves of the axle would have been able to separate and the section of the axle within the gear-side output bearing would still have been able to rotate without causing the observed overheating of the bearing.

D7 The observed high heat input to the GE bearing and labyrinth was not consistent with any heating that could have resulted from two fracture faces rubbing against each other before the axle collapsed. Such heating would need sustained axial force between the rubbing fracture faces, but there is no mechanism to generate such forces between two halves of a fractured axle. There was also no evidence on the undamaged parts of the fracture face that any rubbing had taken place.

D8 Class 222 axles are routinely tested every 300,000 miles (483,000 km) or annually (whichever is sooner) using ultrasonic non-destructive testing to check for any crack-like defects which could compromise the fatigue strength of the axle. The hollow axle allows inspection from inside the bore of the axle which provides a greater sensitivity than the conventional ultrasonic examination technique used on solid axles. Axle E1692/07 was last inspected ultrasonically for cracks on 24 September 2009 and no defects were found. No fatigue cracks have ever been found on Meridian axles.

Seizure of the gears (discounted)

D9 The cardan shaft from the traction motor drives two helical gears on the input side of the final drive gearbox, which drive the pinion gear. The pinion drives the bevel gear mounted on the axle. A seizure of any of these gears, for example due to a broken gear tooth or some other fragment jamming the gears, could have locked the gearbox.

D10 Prior to the strip down of the final drive gearbox, the right-hand half of the axle (ie the half including the gearbox) was noted as being able to rotate freely in the gearbox. Therefore the gears had not seized.

D11 Had the gears been jammed, the axle would have stopped rotating and the wheels would have skidded on the rail head. Frictional heating at the wheel/rail interface would not have caused the observed overheating of the bearings, which would have stopped rotating. The traction system did not detect any faults until after the irregular marks had appeared on the rail head (paragraph 38) and only around 13 seconds before the derailment occurred.

D12 There were no broken teeth on any of the gears. However, there was evidence that a fragment of the gearbox casing from the area where it had been perforated (figure D6) had become jammed between gears, but the perforation was probably consequential as explained later in paragraph D27.

Failure of the GE bearing due to a defect, damage, contamination or incorrect installation (unlikely)

D13 The GE and NGE bearings were examined in detail by bearing experts assisting the investigation. The findings did not indicate that the bearing failure had been caused by a bearing defect, contamination or incorrect assembly. The key evidence supporting this is set out in the following paragraphs. These failure modes cannot be completely discounted as they are common causes of bearing failures; however, they are considered unlikely.

D14 There was no overall appearance of a catastrophic bearing failure. When such failures occur, it is usual for the bearing cage to break and the rollers to lose their radial position in the bearing. Figure D2 shows x-ray images of the gear-side output bearing before it was cut for detailed examination. All the rollers were in place but slightly deformed in shape. The cage was intact (figures D3 and D4).

D15 There was also no evidence of damage to raceways of the failed bearing (figures D3 and D4), such as rolling contact fatigue. Such surface damage can cause bearing seizure.

D16 The corners of the bearing cage did not show any significant wear, indicating that there had not been any significant roller skewing which could otherwise have caused the bearing to seize.

D17 The rollers had become deformed during the last stages of the failure but this deformation was uniform indicating that the bearing had been rotating in the lead up to and after the derailment, until the train had stopped or nearly stopped.

D18 The GE bearing had run for 922,000 miles (1.48 million km) without incident. Had there been some defect with the bearing or its installation, it is very likely the problem would have manifested itself earlier in its life.

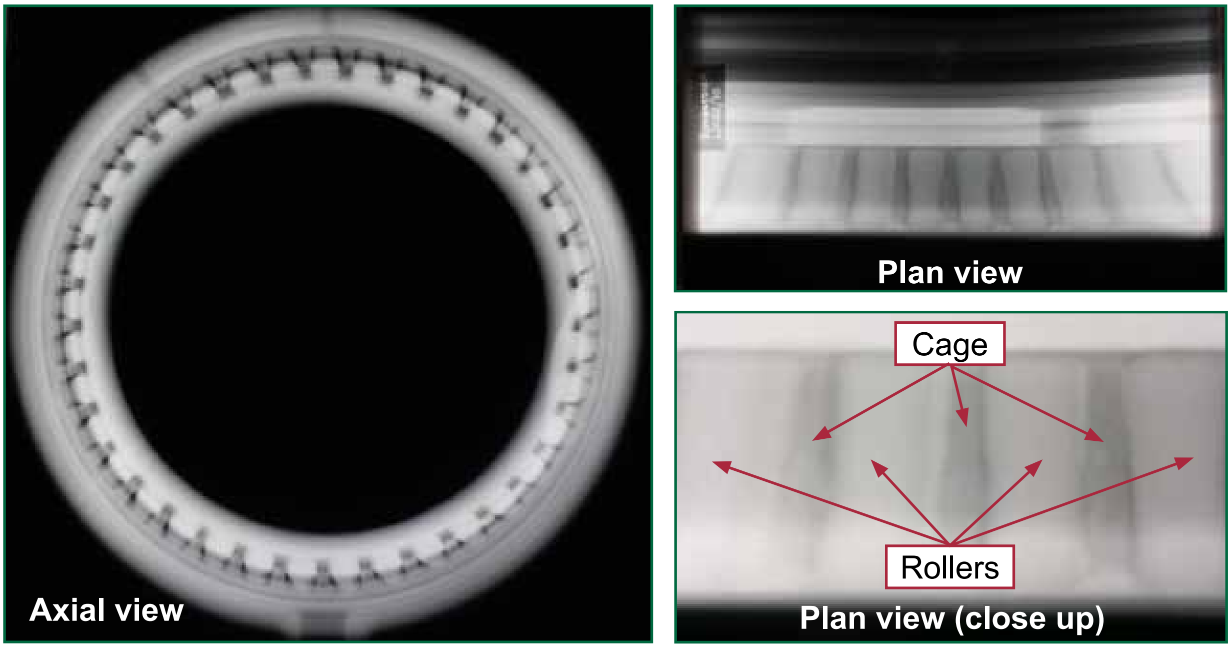



*Figure D2: X-ray images of GE bearing (courtesy of Bombardier Transportation)*


*Figure D3: Segments of the GE bearing (courtesy of ESR)*

## Primary traction rod failure (discounted)

D19 The right-hand primary traction rod, which connects the right-hand axle box to the *bogie frame*, had fractured at some point in time either in the lead up to the derailment or after it. The possibility that this may have happened before the derailment and led to the failure was considered but discounted for the following reasons.

D20 Examination of the fracture faces on the traction rod showed no evidence of a fatigue failure or corrosion, indicating that the rod had broken very recently and under overload. There is no history of such fractures on the Meridian fleet or evidence of an obstacle strike before the derailment which could have applied sufficient longitudinal force to the wheelset to cause the fracture.

D21 It is known that the wheelset struck both a foot crossing and an AWS magnet after derailment. Either of these impacts could have caused the traction rod fracture.

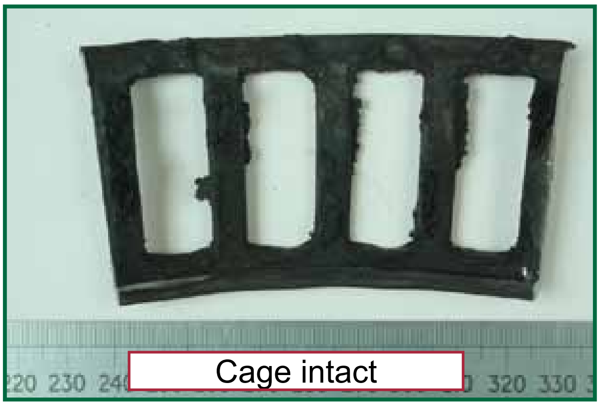
## Loose bearing housing bolts (discounted)

D22 On the GE bearing housing, all of the 12 bolts which secure the housing to the gearbox casing, and which should be tight to a torque of 200 Nm, were found to be loose. Five bolts had reduced torques of between 40 and 110 Nm, five were completely loose and two were missing (figure D5). On the NGE bearing housing, two bolts were loose and the remainder had reduced torques of between 20 and 200 Nm. The possibility that the bolts had been loose before the derailment and that this had initiated a bearing failure was considered and discounted for the following reasons.

D23 None of the bolts had been dismantled since original build because this gearbox had not yet been overhauled. A fleet check of these bolts carried out after the accident did not find any evidence of other gearboxes with multiple loose bolts. The other 13 gearboxes on unit 222005 revealed that 7 bolts (out of a total of 312) distributed over five different gearboxes were slightly loose (still greater than 180 Nm torque). Therefore, there was no evidence of a fleet-wide problem of these bolts becoming loose.

D24 The condition of the gear teeth and the contact patterns between the pinion and gear wheel did not show any indication that the bearing housing had been loose. Had it been so, the bearing would not have been correctly located in the axial direction and this is likely to have shown up on the gear teeth contact patterns.

D25 The external surface of the GE bearing housing is estimated to have reached 350°C – 400°C during the failure. At such high temperatures, some relaxation of the bolt pre-load from the original torque tightening would be expected due to thermal effects as the housing and bolt materials have different coefficients of thermal expansion. A tendency for the housing bolts to lose preload was also noted in the laboratory tests (see appendix E, paragraph E17). Following the derailment, the severe loadings from the impacts with the foot crossing and AWS magnet are likely to have caused the bolted joints to slip at the joint interface and the bolt pre-load to drop further. Once the bolt preload is lost, the bolts are vulnerable to unwinding under vibration.



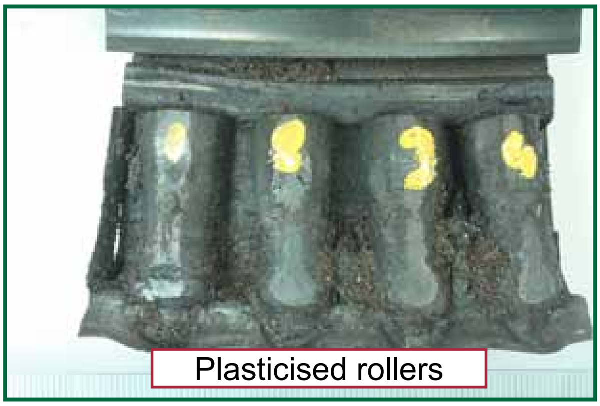




*Figure D4: Close-up of outer raceway, cage and rollers from one segment (courtesy of ESR)*

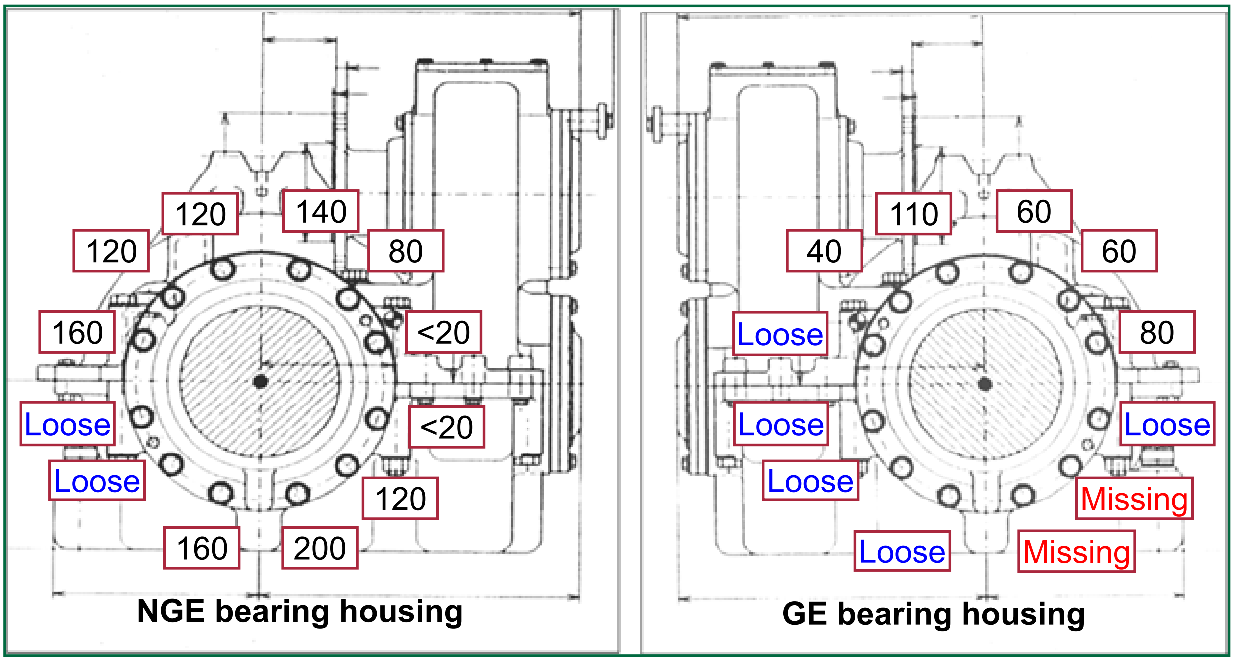



*Figure D5: Loose bearing housing bolts (values above in Nm of torque tightness)*

Failure of the GE bearing due to lack of oil (unlikely)

D26 The oil supply to the gears and bearings in the final drive gearbox provides both lubrication and cooling. Post accident examination of the gearbox revealed that all the oil had drained from the gearbox and there was a puncture to the sump. The question therefore arose as to whether the loss of oil had happened before the derailment (either because the gearbox had not been re-filled with oil at the last maintenance or because it had been punctured while running) or after it.

D27 During the accident the gearbox had dropped down due to the broken axle, and evidence from site indicated it had struck a foot crossing and an AWS magnet and had been in contact with sleepers from time to time. At some point, most likely after the impact with the AWS magnet, the gearbox had also spun round so that it was found upside down after the accident. There were two holes in the damaged gearbox through which the oil could have leaked out:

- A perforation measuring 35 mm wide by 30 mm in the bottom forward face of the oil sump of the gearbox (figure D6). This perforation is likely to have been made in the initial impact with the AWS magnet.
- The top cover plate had been sheared off by contact with the track when the gearbox was upside down. Observations from site are consistent with a band of smeared oil, approximately the width of this top cover plate, on the sleepers.


*Figure D6: Perforation in the bottom of the gearbox*

D28 There was a significant amount of spilled gear oil found on site over a length of approximately 0.5 miles (0.8 km) in the four-foot of the down line, beginning at the demolished AWS magnet (paragraph 40) and extending in the direction of travel. Burnt gear oil has a distinctive smell and could be differentiated from the spilled diesel fuel also on site. This indicated there had been at least a significant proportion of the 5 litre oil capacity in the gearbox at the time of derailment and that the gear oil spilled on site had come from one or both of the available holes, after the impact with the AWS magnet.

D29 The oil sample and oil change work carried out during the last B exam appears to have been carried out competently, initially by a fitter who was familiar with these tasks and then independently checked by another fitter, both of whom signed off the oil change tasks on unit 222005 to confirm they had done the work. There was no evidence that the process of carrying out the oil change work in two separate tasks, before and after the train reversal in the depot (paragraph 30), had caused any omission.

D30 The adjacent gearbox on vehicle 60625 and all the other gearboxes on unit 222005 had new oil to the correct level, which supports the view that there had not been a maintenance error during the B exam which could have resulted in a no oil, low oil or an over-fill condition.

D31 There was no evidence of oil contamination or oil spray on the vehicle underframe around the failed axle, which might otherwise have indicated a leak of oil from a punctured gearbox or labyrinth seal before the derailment.

D32 The oil passages that carry oil from a splash fed gallery at the top of the gearbox to both the GE and NGE bearings, were clear of any blockage.

D33 Comparison with a previous instance of a similar gearbox (from a Class 221 Super Voyager) which was found by Voith to have been run without oil in March 2004, revealed some differences:

- the interior of the East Langton gearbox was still wet with oil, whereas that from the previous failure was reported to be ‘bone’ dry; and
- the paint on the NGE bearing housing on the East Langton gearbox had not overheated and discoloured, whereas in the previous failure, both output bearing housings had discoloured paint.

D34 The conditions of the bevel and helical gears and the other bearings in the gearbox were assessed by a specialist advising the investigation. The condition of these components did not indicate any prolonged running without oil. There was scuffing damage to the surfaces of the bevel gear teeth, the shape and location of which indicated that there had been misalignment in the meshing of the gears. The severity of the scuffing suggested that the period of misaligned running was likely to have been of the order of weeks or months rather than days prior to the derailment. In addition to the scuffing, there were also indentation marks on the teeth which had been caused by ballast debris that had entered the gearbox during the derailment. The generally good condition of the other components did not provide confirmation of the presence of adequate oil in the gearbox since this was also noted in the laboratory tests (appendix E) after the failures due to running with no oil.

D35 The thrust lip on the NGE bearing did not show signs of significant scuffing or wear that would be expected if it had been running for two days (ie since the B exam) without oil. The GE bearing had suffered too much heat damage to be able to assess its condition prior to the accident.

D36 There was a blackish carbon deposit on the interior surfaces of the gearbox casing, axle and NGE bearing, indicating that oil had been falling on these surfaces during the failure. In particular the thrust rib of the NGE bearing (figure D7) had a layer of carbon deposit on the inner race and around the corner of the thrust rib. The thickest part of the layer on the thrust rib was around 40 - 50 μm at the corner (the hottest exposed part of the rib) and tapered down in thickness over the land (figure D8). These deposits indicated that oil had been present while the bearing was running hot. Metal particles found embedded in the layer also indicated that the oil was in liquid rather than vapour form as vapour could not have transported the metal particles onto the surface of the thrust rib.

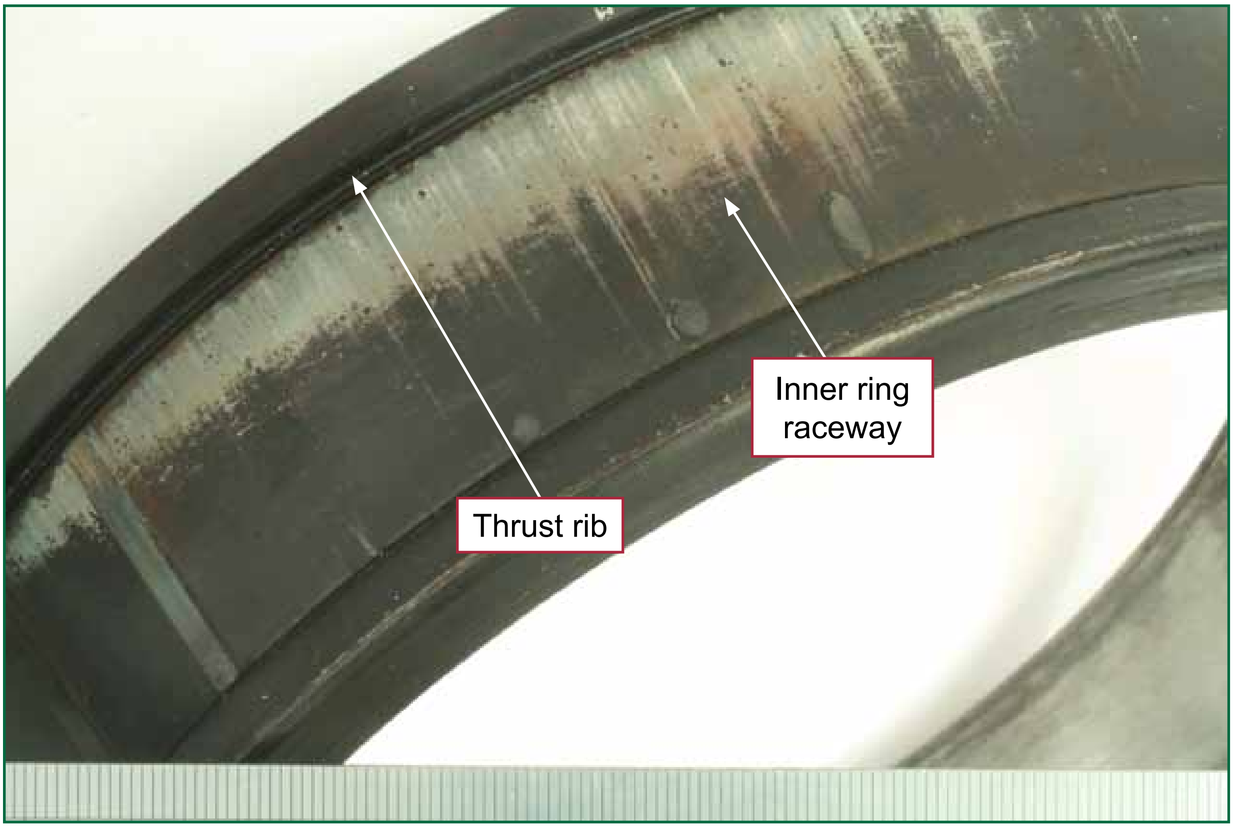



*Figure D7: NGE bearing inner ring thrust rib (courtesy of ESR)*

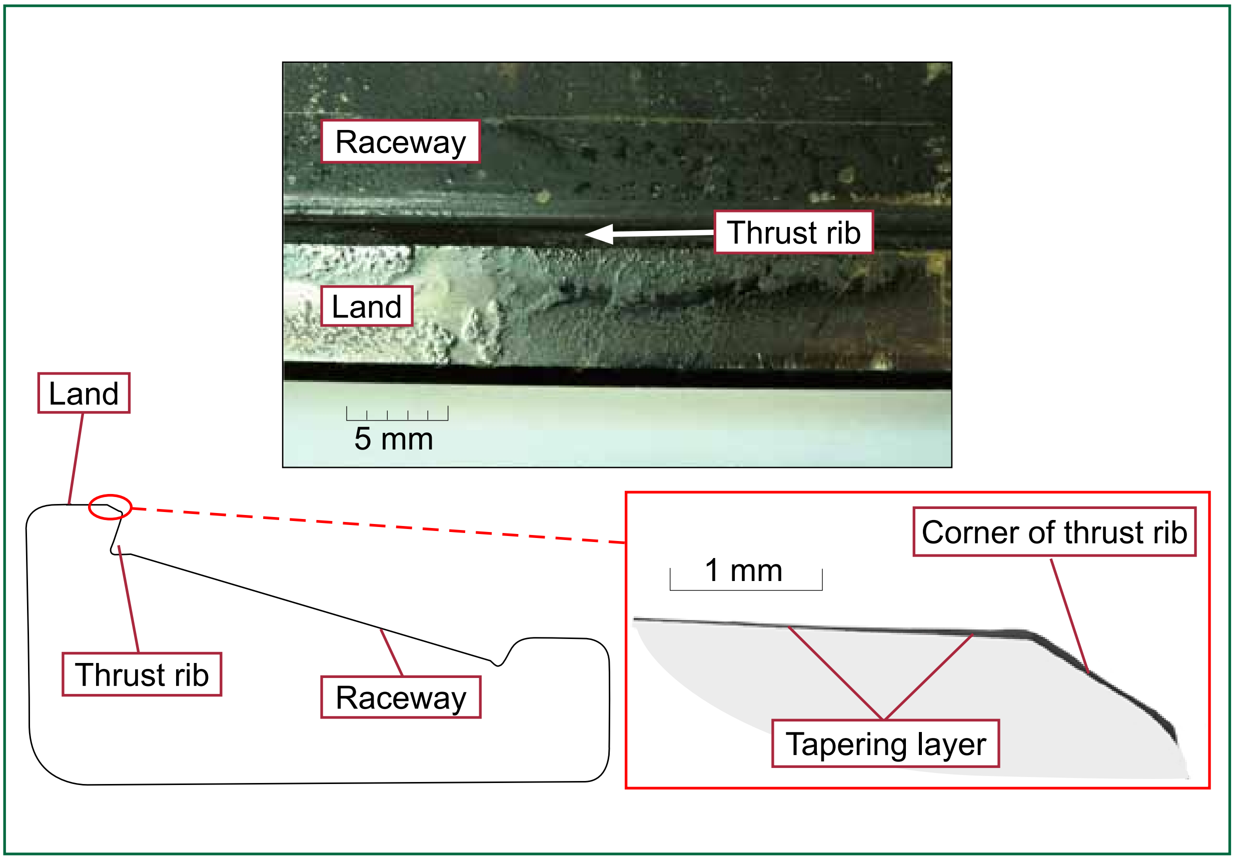



*Figure D8: Carbon deposit on thrust rib of NGE bearing (photograph courtesy of ESR)*

D37 The GE bearing had suffered relatively little damage considering the amount of heat that had been generated at the axle/inner ring interface and the period of time the gearbox had been running overheated. In contrast, damage to the GE bearing observed in a previous service failure caused by running with no oil (paragraph D33) and the damage to the GE bearing of test gearbox 3 after it failed while running with 1 litre of oil (see appendix E), was significantly greater and different in appearance. Although testing on gearbox 3 was stopped a few minutes after failure commenced, there was a significant amount of cage damage and roller material had been transferred to the raceways. This was not seen in the East Langton GE bearing. These differences indicate that the East Langton failure occurred in the presence of oil feed to the output bearings, with the oil assisting in preventing adhesion and welding between the overheated bearing components.

# Appendix E - Description of gearbox laboratory tests and results

## Test Rig

E1 Testing was undertaken at Voith Turbo's test facility in Heidenheim, Germany during 17 January – 3 February 2011. The tests were procured by Bombardier to a specification agreed with the RAIB and Voith, and were witnessed by the RAIB and Bombardier.

E2 The test rig is shown in figure E1. Two gearboxes were tested simultaneously in a back-to-back arrangement. An electric motor (not shown) drove test gearbox A which in turn drove the other test gearbox B by means of a long cardan shaft C. Gearbox B drove another electric motor D acting as the brake. The motors could provide traction or braking in either clockwise or counter clockwise direction. The speed and torque applied to the gearboxes were equal and controlled from a control room. The rotational direction of the two gearboxes was always opposite.

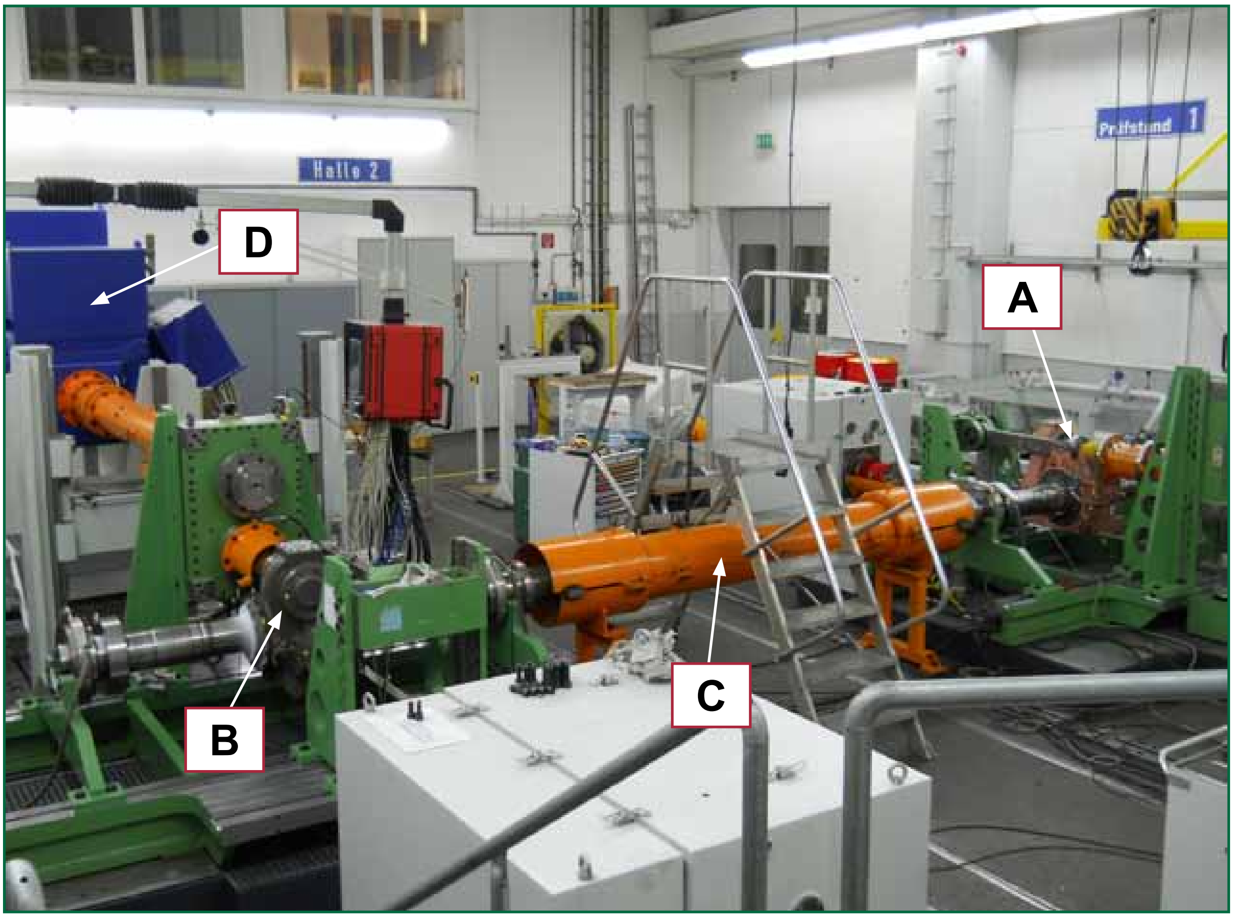



*Figure E1: Test rig*

## Test Gearboxes

E3 Three gearboxes were tested with the following axle/inner ring clearances at the GE bearings:

- Gearbox 1: 77 μm, which was close to the highest found in service (79 μm).
- Gearbox 2: 1558 μm; representing a likely high value of axle/inner ring clearance before a thermal runaway might start, based on research by Nagatomo and Toth[8]. The GE bearing seat on the axle was machined down to obtain this clearance.
- Gearbox 3: 477 μm; representing an intermediate axle/inner ring clearance value. The GE bearing seat on the axle was also machined to obtain this clearance.

Gearbox 1 was installed at position B in figure E1 for the duration of the tests. Gearboxes 2 and 3 were consecutively installed at position A. Each gearbox was filled with 5 litres of oil.

## Instrumentation

E4 Figure E2 shows the instrumentation fitted to gearboxes 2 and 3. Gearbox 1 had the same, except that the axle/inner ring interface temperature measurements (T4 inner and T5 inner) were not fitted. Additional instrumentation was fitted to the test rig for the purpose of monitoring vibrations and temperatures.

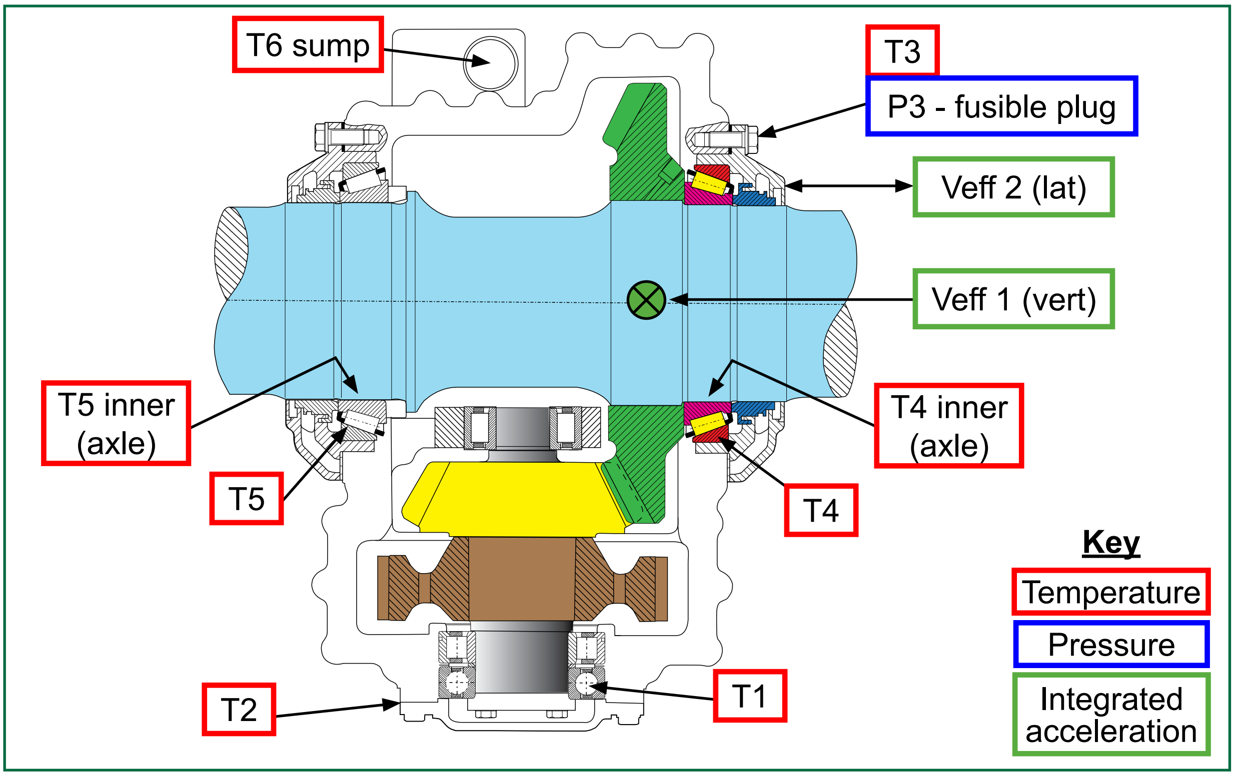



*Figure E2: Arrangement of instrumentation*

## Load cycles

E5 Three different load cycles were used during the test programme:

- 'EMT' load cycle: a simplified one hour block of testing, representative of the torque and speed seen by the gearbox during normal operation on the Midland Main Line. It was based on OTDR data and included slow and high speed running and coasting. One-hour blocks, composed of various torque and speed combinations as shown in table E1, were repeated to form three-hour blocks.

| Input torque (Nm) | Input shaft speed (RPM) | Duration (s) |
|---|---|---|
| 3856 | 430 | 168 |
| 895 | 1900 | 1812 |
| 50 | 1900 | 648 |
| 1500 | 2250 | 468 |
| 2487 | 1450 | 216 |

*Table E1: Torque and speed composition of each one-hour block*

- 'HS-EMT' load cycle: representing constant speed running at the maximum line speed on the Midland Main Line of 110 mph (177 km/h). The input shaft torque and speed were 766 Nm and 2600 rpm respectively. Various durations of running with this load cycle were used during the test programme to assess the reaction of the gearboxes to high speed running.
- '125' load cycle: representing constant speed running at the maximum speed for which the Voyagers and Meridians are certificated (125 mph (201 km/h)). The input shaft torque and speed were 400 Nm and 2960 rpm respectively. Various durations of running with this load cycle were used during the test programme to assess the reaction of the gearboxes to maximum speed running.

E6 Prior to load cycle testing, each gearbox was first 'splash' tested using a standard Voith process which involved driving both gearboxes in the rig at 600 rpm and then 1200 rpm for around 15 minutes in each direction without any load torque. The purpose of this was to flush the interior of the gearbox of any assembly residues or contaminants and to circulate oil around the bearing and gears. After the splash test the gearbox was emptied and refilled with fresh oil. The gearboxes were then taken through a 'running-in' phase with different torque and speed combinations in each direction to help the gears to bed in.

E7 Approximately 80 hours of testing was carried out between 14 January 2011 and 3 February 2011, initially with gearboxes 1 and 2 and then with gearboxes 1 and 3. For the majority of the test programme gearboxes 2 and 3 were run in traction mode with their input shaft rotating in a counter clockwise direction, as this produced the highest output bearing temperatures. Correspondingly, gearbox 1 was run mainly in braking mode and with its input shaft running in the clockwise direction. A test log is contained in table E2.

| Date | Summary of testing |
|---|---|
| *Gearboxes 1 and 2 (initial oil fill 5 litres)* | |
| 14/01/11 | Splash test on gearboxes 1 and 2 (1 hr) |
| 18/01/11 | Running in test on gearboxes 1 and 2 (1 hr) |
| 19/01/11 | 'EMT' load cycle testing (9 hrs) |
| 20/01/11 | 'EMT' load cycle (9 hrs) |
| 21/01/11 | 'EMT' load cycle (12 hrs) |
| 24/01/11 | 'EMT' load cycle (9 hrs)<br>'125' load cycle (1.5 hrs) with cooling fan on GE bearing which recorded an abnormally high temperature |
| 25/01/11 | 'EMT' load cycle (12 hrs) |
| 26/01/11 | Standard Voith series test (1 hr); 3000 rpm in each direction with no load<br>'EMT' load cycle for 2 hrs followed by 'HS-EMT' load cycle for 1 hr (ie total 3 hrs) at 7, 4, 3 litres of oil fills on gearbox 2. Gearbox 1 oil fill was maintained at 5 litres throughout. |
| 27/01/11 | 'HS-EMT' load cycle with gearbox 1 at 5 litres and gearbox 2 at 2 litres oil (3 hrs)<br>'HS-EMT' load cycle with gearbox 1 at 5 litres and gearbox 2 at 1 litre oil. Gearbox 2 failed after 110 minutes. |
| *Gearboxes 1 and 3 (initial oil fill 5 litres)* | |
| 28/01/11 | Installation of gearbox 3 in test rig<br>Splash test of gearbox 3 which failed after 22 minutes due to excessive vibration and rapid rise of output bearing temperatures. Further testing abandoned. |
| 31/01/11 | No testing due to failure of gearbox 3 |
| 01/02/11 | Strip down and examination of gearbox 3<br>Reassembly of gearbox 3 with new GE bearing and re-installation in test rig<br>Splash testing of gearboxes 1 and 3 (1 hr) |
| 02/02/11 | Running-in test for gearbox 3 (1 hr)<br>'HS-EMT' load cycle (1 hr)<br>'125' load cycle (0.3 hr) with cooling fan on GE bearing. Gearbox 3 registered abnormally high GE and NGE bearing temperatures. Telemetry system failed and rig was stopped for repair.<br>Resumed testing with '125' load cycle (1.5 hrs) |
| 03/02/11 | Repeat of 02/02 testing with 'HS-EMT' load cycle (1 hr) followed by '125' duty cycle (1 hr) to repeat high temperature obtained before telemetry failure<br>'125' duty cycle with gearbox 1 and 3 at 3 litres of oil (1 hr)<br>'125' duty cycle with gearbox 1 at 5 litres oil and gearbox 3 at 1 litre oil (2.5 hrs)<br>Removed further oil from gearbox 1 (now at 0.75 litres) and changed direction of rotation<br>'125' mph duty cycle. Gearbox 3 failed after 26 mins with fusible plug activation. |

*Table E2: Test log*

## Oil sampling

E8 A total of 55 oil samples were taken from the gearboxes during the tests. The oil removed for each sample was replenished with new oil to maintain the overall oil level in each gearbox. Additionally, seven oil samples were taken from gearbox 1 on 20 January at nominal intervals of 30, 60, 90, 120, 180, 240 and 650 minutes after testing was stopped, in order to assess how the oil samples varied with time. All oil samples were analysed subsequently to determine:

- metal content (iron, chrome, zinc, aluminium, nickel, copper, lead);
- non-metallic content (silicon, potassium, sodium) ;
- particle quantifier index (PQI); and
- viscosity (at 40°C and 100°C).

## Findings

### *Gearbox 1*

E9 Gearbox 1 completed around 80 hrs on the test rig. The peak GE bearing temperatures were around 120°C for the '125' load cycle and 110°C for the 'HS-EMT' load cycle. There was no indication of abnormal temperature rises during testing.

E10 When its oil fill was reduced to 3 litres on 3 February for 1 hour of running under the '125' load cycle oil, there was no indication of elevated temperatures; the peak temperature of the GE and NGE output bearings (outer rings) being 110°C and 100°C respectively.

E11 Oil sample data from gearbox 1 did not show any abnormally high values although there was evidence of wear metals on the magnetic dipstick at each oil sample. The maximum iron reading was 107 parts per million (ppm), obtained on 24 January with a corresponding PQI of 33. The maximum PQI was 60 on 20 January with a corresponding iron reading of 89 ppm.

E12 When gearbox 1 was stripped down, all the gear and bearing components were found to be in a generally good condition. There was evidence of rotation of the GE bearing inner ring on the axle but there was no evidence of overheating. The axle diameter had reduced by 6 µm and the bearing bore had increased by 2 µm due to wear during the tests, which represented 3,915 miles (6,300 km) of running. Assuming a similar load cycle and wear rate in service, an increase in axle/inner ring clearance of around 400 µm per year would be expected, based on an average annual distance travelled by Meridians of 215,000 miles (346,000 km).

### Gearbox 2

E13 Gearbox 2 completed around 69 hours on the test rig. The GE bearing temperature generally remained below 100°C while running on the 'EMT' and 'HS-EMT' load cycles. When subjected to the '125' load cycle with normal oil fill, gearbox 2 ran hotter; the GE bearing temperature reached 145°C at the axle/inner ring interface and 140°C on the outer ring. Despite the abnormally high temperature, it remained stable and there was no indication of a thermal runaway developing. The NGE bearing temperature did not rise at the same rate and remained below 121°C.

E14 Increasing the oil fill to 7 litres or reducing the oil to 4 litres and then 3 litres did not have a significant effect on the output bearing temperatures. At 2 litres of oil, there was a drop in temperature to 100°C on the outer ring of the GE bearing. When the cooling fan was switched on, there was a noticeable rise in temperature at both the GE and NGE bearing, to 120°C and 109°C respectively. This tendency for the output bearing temperatures to rise when cooling air was directed at the casing was also noted on gearbox 3 (paragraph E20) and is discussed at paragraphs 88 and 91.

E15 At 1 litre of oil, the gearbox ran for around 100 minutes without incident but shortly after the cooling fan was switched on, the GE bearing temperature rose sharply to around 250°C (figure E3) and then it failed. The NGE bearing temperature had also risen from around 112°C to around 150°C.

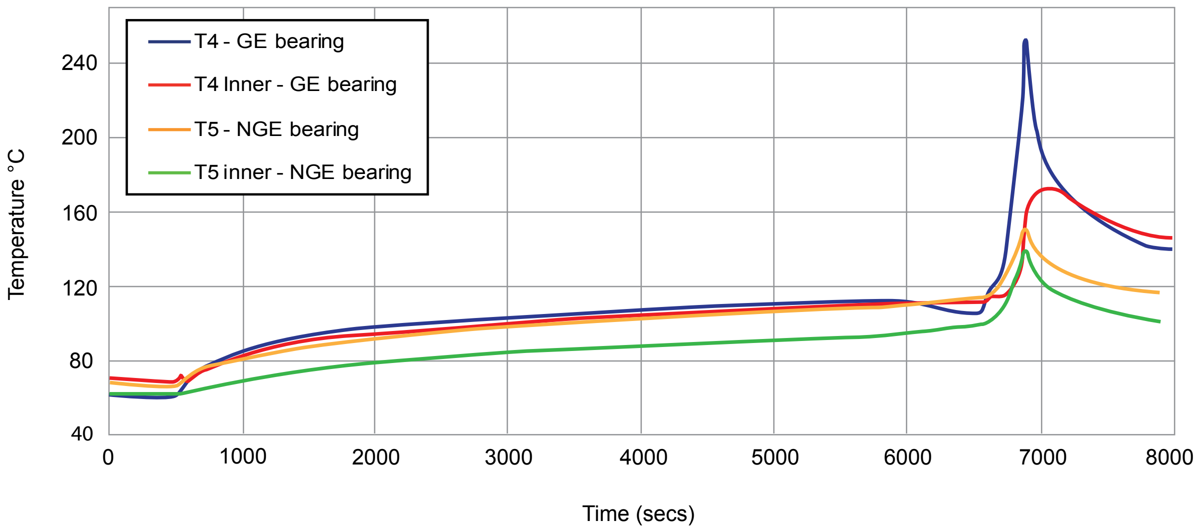



*Figure E3: Output bearing temperature rise of gearbox 2 at failure with 1 litre oil*

E16 Oil sample data from gearbox 2 did not show any abnormally high values, although there was always evidence of wear metals being generated on the magnetic dipstick. The maximum iron reading was 73 ppm on 20 January, with a PQI of 150 when running with normal oil level. After failure with 1 litre of oil, the maximum iron reading was 175 ppm and the PQI was 119.

E17 When gearbox 2 was stripped down the gears were found to be in good condition with no scuffing of the bevel gears and some minor indentation damage on the helical gears due to debris from the failing bearing. The seat of the GE bearing on the axle was covered in fretting residue and there was evidence of metal pick-up and welding between the inner ring and the abutment face of the adjacent gear wheel, indicating that the inner ring had been rotating relative to the axle and stopping from time to time. The GE bearing rollers were deformed (figure E4) and there was heavy metal smearing on the outer raceway. The torque tightness of 7 of the 12 bolts securing the gear-side output bearing housing were noted to have reduced (to between 140 and 190 Nm) from the nominal assembly torque tightness of 200 Nm.


*Figure E4: GE bearing from gearbox 2 after failure at 1 litre oil showing rollers and cage (A) and smeared material on outer raceway (B)*

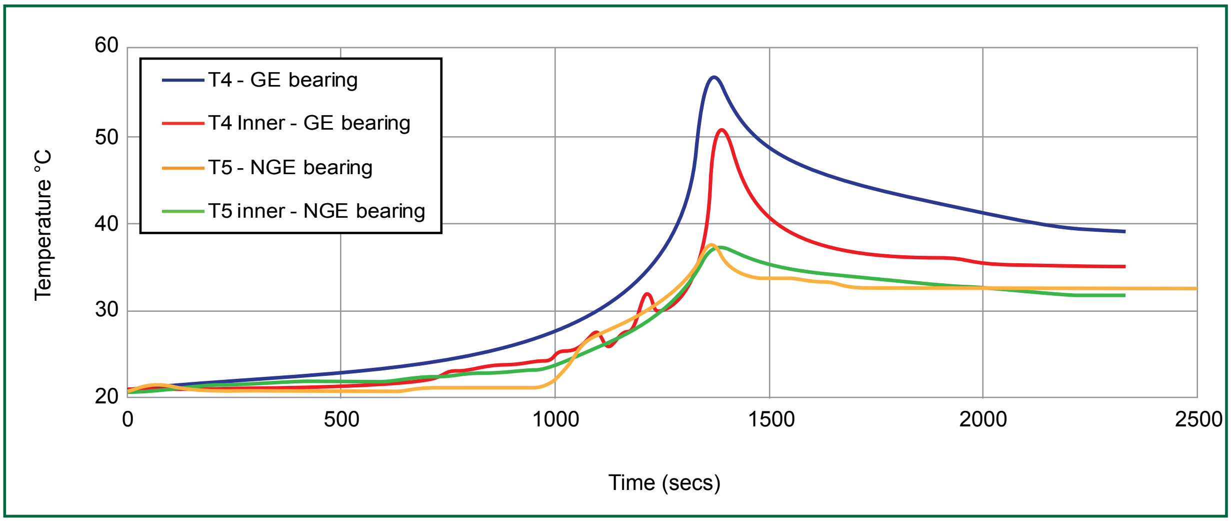



*Figure E5: Output bearing temperature rise of gearbox 3 during splash test (normal oil level)*

## Gearbox 3

E18 Gearbox 3 completed 10.4 hours on the test rig. The test time was limited by failure of the gearbox during the initial splash test and problems with the functioning of the telemetry system used to measure the inner ring temperatures.

E19 The splash test failure occurred 22 minutes into the run, shortly after increasing the speed from 600 to 1200 rpm. At this point, the gearbox ran with excessive vibration and there was a rapid rise of the GE bearing inner and outer ring temperatures up to 58°C (figure E5). There were also rapid rises of the NGE bearing temperatures. The gearbox was removed from the rig, stripped down and re-assembled with a new GE bearing and then re-installed in the rig.

E20 On restarting the testing, the splash test, running-in test and 1 hour of the ‘HS-EMT’ load cycle were completed without incident, with all temperatures remaining below 100°C. The loading was then changed to the ‘125’ load cycle and the cooling fan was switched onto the GE bearing. A further incident of rapidly rising GE and NGE output bearing temperatures (to 143°C and 130°C respectively), occurred 20 minutes later (figure E6). The telemetry system failed at this point and the test was stopped to carry out repairs.

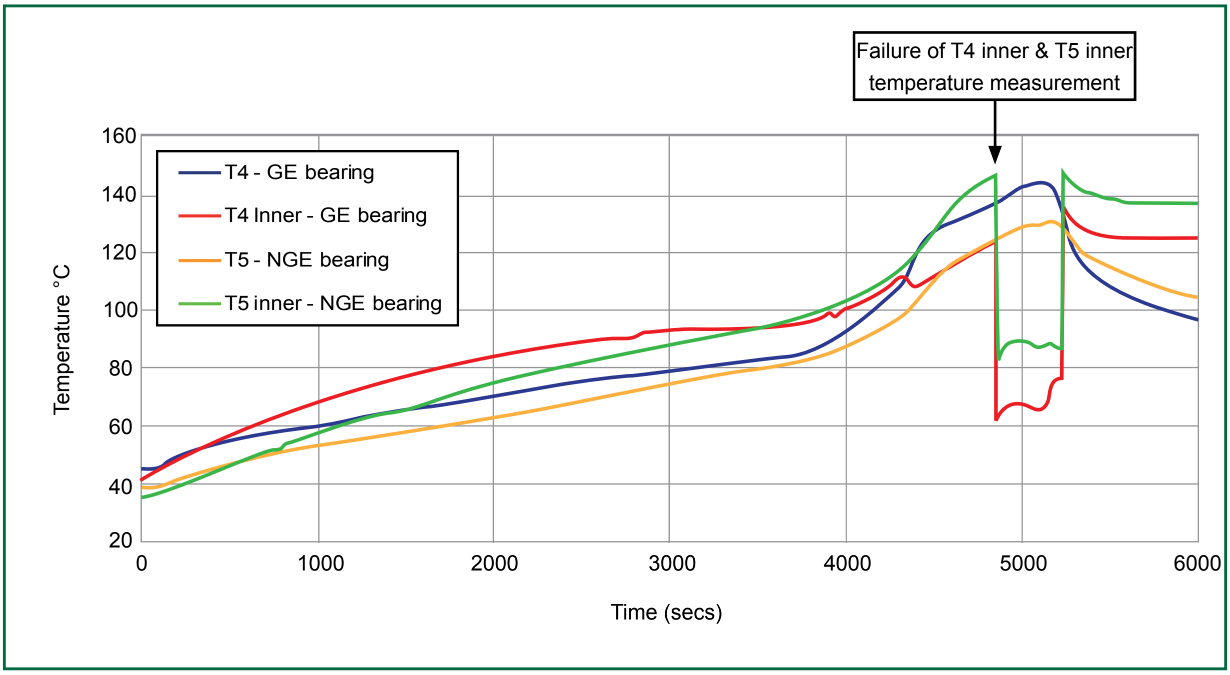



*Figure E6: Output bearing temperature rise of gearbox 3 during '125' load cycle (normal oil level)*

E21 When testing was restarted (without a functioning telemetry system), the same sequence of loading was repeated to see if the high temperature incident could be repeated. However, the gearbox ran smoothly and the peak temperature only reached 95°C. The difference in maximum operating temperature from one day to the other under almost identical test conditions, was nearly 50°C.

E22 Due to constraints on the availability of the test rig, further testing of gearbox 3 with normal oil fill had to be curtailed. Running with 3 litres did not cause a significant increase in bearing temperature. The oil was further reduced to 1 litre to induce a failure and test the fusible plug. Gearbox 3 failed after a total running time of 3 hours with 1 litre of oil (with and without the cooling fan). As with gearbox 2, failure started with a rapid rise in GE bearing temperature up to 289°C. The speed was reduced at this point from 2960 rpm to around 1600 rpm to prevent damage to the test rig and then increased again to 2500 rpm. The fusible plug activated around 210 seconds after the first rapid rise in GE bearing temperature.

E23 None of the three oil samples taken from gearbox 3 before the failure showed excessively high values. The iron readings just before and after the bearing failure, were 58 and 87 ppm respectively, and the corresponding PQI values were 61 and 340.

E24 On strip down, the bevel and helical gears were found to be in good condition generally, but slightly worse than gearbox 2. On the axle there was a significant amount of welding on the seat of the GE bearing and the abutment face of the gear wheel, indicating that the bearing inner ring had been spinning on the axle. The inner ring of the labyrinth seal had also spun on the axle as a result of touching down on the outer ring of the labyrinth seal during the failure.

E25 The GE output bearing was severely damaged (figure E7). The cage was broken and the rollers were skewed in the raceway and deformed, particularly at the ends running on the thrust rib, which had become rounded. There was also heavy metal smearing on the outer raceway.


*Figure E7: GE bearing from gearbox 3 after failure showing rollers and cage (A) and smeared material on outer raceway (B)*

## Appendix F - Relevant Meridian alarm systems

F1 There are two on-board systems on the Meridians which give information about train faults to the driver:

- alarm panel; and
- TMS screen.

F2 The alarm panel on the driver's desk has 10 push buttons; five red (safety critical) and five yellow (non-safety critical) as shown in figure F1. The push buttons illuminate when a fault is detected (table F1) and sound a buzzer. Depressing the button cancels the alarm. All of the alarms are hard wired and are independent of the Train Management System (TMS).

| **Safety critical faults (red):** | **Non safety critical (yellow):** |
|---|---|
| a) Fire<br>b) Bogie fault<br>c) Track circuit assister fault<br>d) Brake fault<br>e) Spare | f) Data recorder fault<br>g) Wheel slip activity<br>h) Safety system isolated<br>i) TMS level 3 fault (generated by any safety critical fault a - d)<br>j) Spare |

*Table F1: Faults associated with the 10 push buttons on the Meridian alarm panel*

One yellow button is labelled 'TMS level 3 alarm', which illuminates at the same time as any red fault lamp and provides a link between the red fault alarms and the TMS system. Whenever a red fault alarm is generated, a separate sensor generates a yellow TMS level 3 alarm to indicate that the TMS has detected a safety critical or service fault. Depressing the yellow TMS level 3 fault button cancels the alarm and acknowledges the fault to the TMS. This is visible once the driver activates the TMS screen (figure F1) by touch.

F3 The TMS computer supervises and monitors the condition of the train's electrical and electronic systems. It has an advisory role and is not safety critical. One of its functions is to log alarms and to make diagnostic information available to the driver via the touch screen.

F4 The TMS screen displays faults and alarm events, which are called anomalies. Anomalies are listed on a separate window of the TMS screen which the driver can access by touching the anomaly button on the TMS screen menu. Unacknowledged level 3 alarms blink on the anomalies window of the TMS screen and appear at the top of the list; acknowledged alarms remain steady and are listed underneath, in the order they appeared.


*Figure F1: Meridian driver's console warning lights and TMS touch screen*

F5 When the safety critical red 'bogie fault' lamp illuminates, the TMS anomaly window will display the source of the fault which can be one or more of three conditions:

- hot axle box;
- broken cardan shaft; and
- air suspension deflated.

The yellow TMS level 3 fault lamp will also illuminate. The driver can use this to cancel the alarm and acknowledge the fault on the TMS anomaly screen.

F6 There are also other TMS screens distributed throughout the train, in the galley, the train manager's office, and the retail area (bar), which display information for use by the train manager.

F7 The driver uses the TMS screen as part of the train preparation duties, but once in motion the TMS screen will normally be blank in order to minimise distractions to the driver.

F8 Table F2 lists the alarms generated during the accident and the responses which East Midlands Trains' operating procedures required the driver to make.

| Fault condition | Indications in cab | Driver action required | Information available on TMS anomaly window |
|---|---|---|---|
| Bogie fault | ● Red bogie fault lamp lit<br>● Yellow TMS level 3 fault lamp lit<br>● Audible alarm | 1. Acknowledge and silence the audible alarm by pressing the lit red and yellow buttons;<br>2. Bring train to an immediate stand at the first safe and suitable location;<br>3. Once it is at a stand, interrogate the TMS screen to identify the defect and vehicle affected; and<br>4. Contact the signaller to advise of the situation. | Type of bogie fault detected which can be one or more of the following:<br>- hot axle box<br>- broken cardan shaft<br>- deflation of suspension<br>Car on which fault located |
| Fire | ● Red fire fault lamp lit (steady if fire is in an engine bay or flashing if internal)<br>● Yellow TMS level 3 fault lamp lit<br>● Audible alarm<br>● Fire alarm sounding continuously | 1. Bring train promptly to a stand at the first safe and suitable location;<br>2. Silence the audible alarm and acknowledge the fault by pressing the lit red and yellow buttons (this can be done whilst driving); and<br>3. Contact signaller to advise of situation.<br>(NB: The driver cannot silence the fire alarm sounders; this can only be done from the source vehicle.) | Fire detection system has been activated, and<br>Location of fire alarm activation |
| PCA<br>(pass com) | ● Pass com/Door Activated fault lamp lit;  (this is on a separate panel)<br>● Yellow TMS level 3 fault lamp lit<br>● Audible alarm<br>● Automatic enhanced brake activation (which can be overridden to prevent train stopping in unsuitable location)<br>● Sound transmitted from microphone at pass com activation point | 1. Acknowledge and silence the TMS level 3 alarm by pressing the lit yellow fault lamp button;<br>2. Bring the train to a stand in accordance with the Rule Book;<br>3. Interrogate the TMS to identify location of pass com activation;<br>4. Talk to the person who activated the pass com via handset in cab - this can be done whilst train is braking but priority to be given to stopping train; and<br>5. Contact signaller to advise of situation. | The location and car on which the pass com operated. |

*Table F2: Alarms generated during the derailment and required driver actions*

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