RAIB
Rail Accident Investigation Branch

Rail Accident Report

Collision between two trams at Shalesmoor, Sheffield
22 October 2015

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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.

Any enquiries about this publication should be sent to:

RAIB
The Wharf
Stores Road
Derby UK
DE21 4BA

Email: enquiries@raib.gov.uk
Telephone: 01332 253300
Fax: 01332 253301
Website: www.gov.uk/raib

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Preface

The purpose of a Rail Accident Investigation Branch (RAIB) investigation is to improve railway safety by preventing future railway accidents or by mitigating their consequences. It is not the purpose of such an investigation to establish blame or liability. Accordingly, it is inappropriate that RAIB reports should be used to assign fault or blame, or determine liability, since neither the investigation nor the reporting process has been undertaken for that purpose.

The RAIB's findings are based on its own evaluation of the evidence that was available at the time of the investigation and are intended to explain what happened, and why, in a fair and unbiased manner.

Where the RAIB has described a factor as being linked to cause and the term is unqualified, this means that the RAIB has satisfied itself that the evidence supports both the presence of the factor and its direct relevance to the causation of the accident. However, where the RAIB is less confident about the existence of a factor, or its role in the causation of the accident, the RAIB will qualify its findings by use of the words 'probable' or 'possible', as appropriate. Where there is more than one potential explanation the RAIB may describe one factor as being 'more' or 'less' likely than the other.

In some cases factors are described as 'underlying'. Such factors are also relevant to the causation of the accident but are associated with the underlying management arrangements or organisational issues (such as working culture). Where necessary, the words 'probable' or 'possible' can also be used to qualify 'underlying factor'.

Use of the word 'probable' means that, although it is considered highly likely that the factor applied, some small element of uncertainty remains. Use of the word 'possible' means that, although there is some evidence that supports this factor, there remains a more significant degree of uncertainty.

An 'observation' is a safety issue discovered as part of the investigation that is not considered to be causal or underlying to the event being investigated, but does deserve scrutiny because of a perceived potential for safety learning.

The above terms are intended to assist readers' interpretation of the report, and to provide suitable explanations where uncertainty remains. The report should therefore be interpreted as the view of the RAIB, expressed with the sole purpose of improving railway safety.

The RAIB's investigation (including its scope, methods, conclusions and recommendations) is independent of any inquest or fatal accident inquiry, and all other investigations, including those carried out by the safety authority, police or railway industry.

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Collision between two trams at Shalesmoor, Sheffield, on 22 October 2015

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Summary

At 08:25 hrs on 22 October 2015, Sheffield Supertram 120 collided with tram 118 which was stationary in the tram stop at Shalesmoor. A number of passengers and a member of staff received minor injuries, and the tramway through Shalesmoor was closed for the remainder of the day.

The collision occurred in conditions of low rail head adhesion on the approach to Shalesmoor tram stop at the time. Tram 120 was not being driven in a manner appropriate for the conditions, and its brakes did not provide the level of braking the driver expected. An additional factor was that at the time, tram 118 was at the tram stop and had not been able to depart prior to the collision because it was blocked by road traffic queuing at a yellow box junction ahead.

As a result of this investigation the RAIB has made one recommendation for UK tram operators relating to reviewing and where necessary improving, their processes for managing the risks from low adhesion conditions.

The RAIB has also identified one key learning point relating to the performance of magnetic track brakes when the rail head has low adhesion.

Introduction

Key definitions

1 Metric units are used in this report, except when it is normal practice to give speeds and locations in imperial units. Where appropriate the equivalent metric value is also given.

2 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. Sources of evidence used in the investigation are listed in appendix C.

The accident

Summary of the accident

3 At 08:25 hrs on Thursday 22 October 2015, tram 120 collided with the rear of tram 118 at Shalesmoor tram stop (figure 1 and 2) on the Sheffield Supertram system. Tram 118, travelling *inbound* from Middlewood, was stationary in the stop at the time. Tram 120 was also travelling inbound, its journey originating at Malin Bridge. Tram 120 was travelling at approximately 8 mph (13 km/h) at the point of collision. Figure 3 shows the trams immediately after the collision.

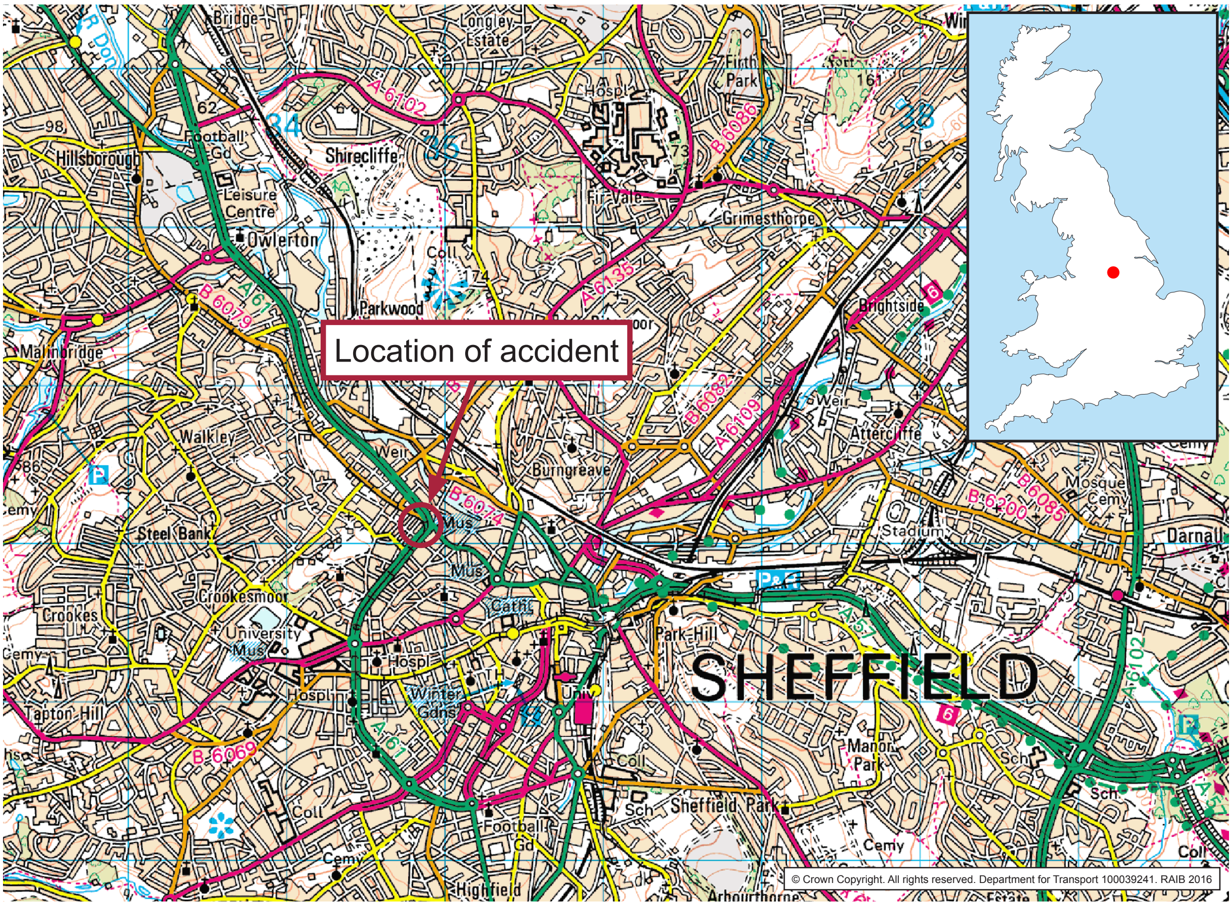

Figure 1: Extract from Ordnance Survey map showing location of accident

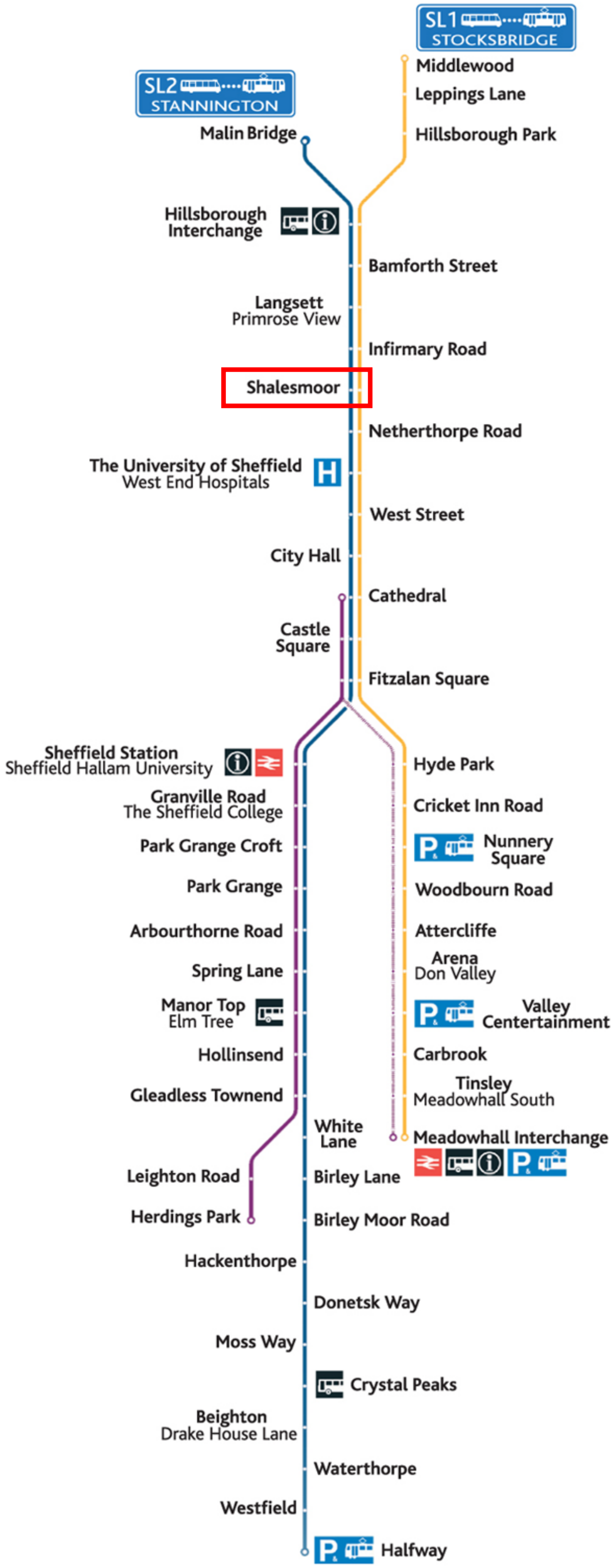

Figure 2: The Sheffield Supertram network and location of Shalesmoor tram stop (image courtesy of Stagecoach Supertram)

Figure 3: The two trams immediately after the collision (photo courtesy of Sheffield Star)

4 A member of Stagecoach Supertram staff and fifteen passengers received minor injuries as a consequence of the collision. Both trams were seriously damaged, and the tramway through Shalesmoor was closed for the remainder of the day while recovery of the damaged trams took place.

Location

5 Approaching Shalesmoor from Hillsborough (figure 2), the tramway is an integrated on-street system; this means that trams share the roadway with motor vehicles. At Shalesmoor, the tramway leaves the road and enters a segregated infrastructure, running along the *median strip* of Netherthorpe Road towards Sheffield city centre (figure 4).

6 The speed limit for trams running on the integrated on-street sections from Hillsborough up to the final approach to Shalesmoor is 30 mph (48 km/h), which is the same speed as that for general road traffic in the area. For the final approach to Shalesmoor tram stop, trams are subject to a 20 mph (32 km/h) limit from 224 metres before the tram stop and then a further limit of 15 mph (24 km/h), from 56 metres before the tram stop (figure 8).

7 The system is laid to *standard gauge* and is electrified on the overhead line system with trams being supplied with 750v DC.

Organisations involved

8 Stagecoach Supertram is the operator of the Sheffield Supertram network and is responsible for all tram and infrastructure maintenance. It is also the employer of the tram drivers, conductors and maintenance staff.

9 South Yorkshire Passenger Transport Executive (SYPTE) owns the Supertram infrastructure and the trams. It lets the concession for system operation to Stagecoach Supertram.

10 Both organisations freely co-operated with the investigation.

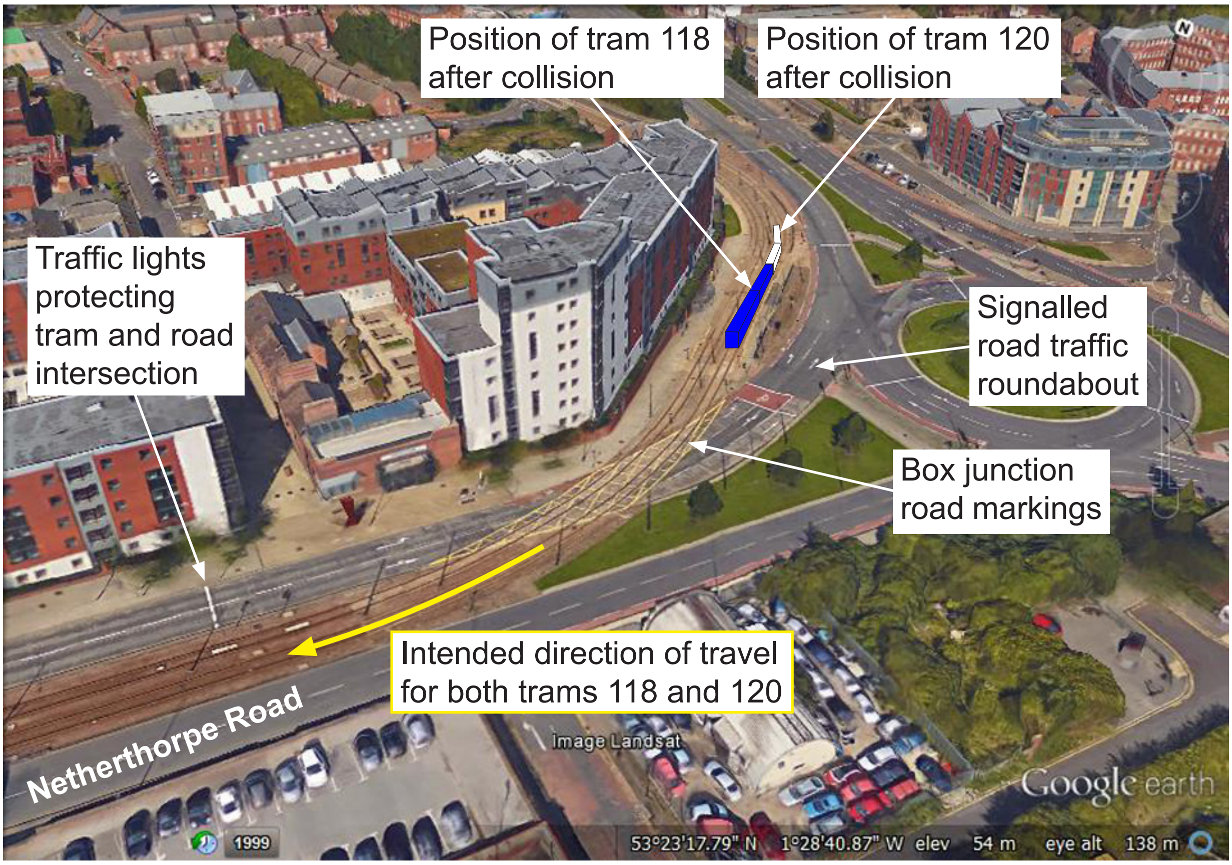

Figure 4: Google Earth view of Shalesmoor tram stop area

Trams involved

11 The trams currently operating on the Sheffield Supertram network (figure 5) were built in 1992 by Siemens-Duewag (now trading as Siemens) at its factory in Dusseldorf, Germany. Each tram comprises three articulated passenger carrying sections, supported on four bogies. A tram is 35 metres long and weighs 52 tonnes empty. The RAIB examined the processes and procedures used for tram maintenance, and the defect history for tram 120. No evidence was found that the maintenance of the tram contributed to the accident.

Rail equipment/systems involved

12 The tramway in the vicinity of Shalesmoor is laid using *grooved rails*. These rails were replaced as part of a planned maintenance programme during September and October 2013. The magnetic properties of the replacement rail, which can affect the performance of the magnetic track brakes (paragraph 32), are the same as that of the original rails installed when this section of tramway was opened in 1995.

Staff involved

13 Each tram carried a driver and two conductors.

14 The driver of tram 120 had been driving trams at Sheffield for more than 20 years. He had been passed as competent to drive Sheffield trams in his last assessment in June 2015.

Figure 5: A typical Sheffield tram

External circumstances

15 The environment around Shalesmoor is urban. The last rainfall before the accident was around 17:30 hrs on 21 October 2015. Sunrise on 22 October 2015 was at 06:44 hrs. The day of the accident was cloudy, and this, combined with the topography of the area, meant that drivers of inbound trams arriving at Shalesmoor were not dazzled by the rising sun.

16 There are a number of large trees to the west of Infirmary Road, leading up to Shalesmoor, from which fallen leaves tend to collect in the vicinity of Shalesmoor tram stop. When crushed by rail vehicle wheels onto the rail head, fallen leaves can significantly reduce the available wheel/rail adhesion. This is discussed further in paragraph 56.

17 The weather conditions before the accident were such that there was a strong likelihood dew had formed on the rail head. This is discussed further in paragraph 57.

The sequence of events

Events preceding the accident

18 Before the start of tram services at around 05:30 hrs on 22 October 2015, the Stagecoach Supertram facilities team attended Shalesmoor tram stop to blow leaves away to help prevent contamination of the rails. The facilities team are responsible for the maintenance of the tram stops and related infrastructure,

19 At 05:54 hrs on 22 October 2015, the driver of tram 120 departed from the Supertram depot, having booked on duty a few minutes earlier. He drove the tram to Malin Bridge, and then operated a 'Blue Route' service (figure 2) travelling from Malin Bridge to Halfway and returning to Malin Bridge.

20 Tram 120 was timetabled to leave from Malin Bridge at 08:11 hrs as another Blue Route service to Halfway, but it departed late at 08:16 hrs.

21 Tram 118 left the park & ride station at Middlewood on time at 08:13 hrs. This was a 'Yellow Route' service (figure 2).

22 The Blue Route from Malin Bridge and the Yellow Route from Middlewood share the same track route after a junction at Hillsborough (figure 2). South of Hillsborough, tram 120 should have preceded tram 118. However, because tram 120 was running late, it ran behind tram 118. Tram 120 departed from Hillsborough around 70 seconds behind tram 118, with both trams travelling inbound towards Sheffield city centre.

Events during the accident

23 When ready to depart from Shalesmoor tram stop, the driver of tram 118 was unable to proceed further towards Sheffield city centre because road traffic was obstructing the yellow box junction ahead of it. Tram 118 was heavily laden with all seats taken and many passengers standing.

24 At 08:25 hrs, tram 120, which had every seat taken and a few standing passengers, collided with the rear of tram 118, 36 seconds after tram 118 had come to a stop at Shalesmoor. The normal *dwell time* at this tram stop is approximately 10 seconds. The driver of tram 120 had tried unsuccessfully to bring his tram to a stop before the collision.

Events following the accident

25 Following the collision, passengers and staff left both trams. Other Stagecoach Supertram staff attended the accident site and provided support to the passengers and staff involved. A member of staff was taken to hospital, but not detained. The remainder of the passengers continued their journeys by other means.

26 Stagecoach Supertram engineering staff carried out necessary repairs to allow both trams to be moved from Shalesmoor. However, difficulties were encountered due to the nature of the damage to tram 118 and it was not possible to move it until overnight into 23 October. Consequently, the tram route through Shalesmoor was closed for the remainder of 22 October.

27 There was no damage to the tramway infrastructure at Shalesmoor.

Key facts and analysis

Background information

<u>The operation of Sheffield Supertram</u>

28 Sheffield Supertram is operated as a *line-of-sight* tramway on which trams must be able to stop before any obstruction ahead. Therefore, the driver must be vigilant for any such obstruction, and the trams must be fitted with a braking system which will allow the driver to stop the tram before an obstruction.

29 There are several sections of the Sheffield Supertram network where tram operation is integrated with public road traffic. Trams are therefore also subject to the laws and regulations governing road traffic in those areas.

30 At intersections, and other potential points of conflict between road vehicles and trams, specific signals are provided to authorise trams to proceed when appropriate. Such signals are provided at Shalesmoor to authorise trams to proceed inbound from the tram stop across the northbound carriageway of Netherthorpe Road (figure 2).

31 Trams interact with the road traffic signal system by means of Vehicle Identification System (VIS) loops. These are inductive loops buried in the road surface which detect the presence of a tram.

<u>Tram braking systems</u>

32 The trams are fitted with three braking systems:

- An *electrodynamic brake* which generates brake force by the action of the vehicle traction motors. This system uses the tram's traction motors (acting as generators) to convert the kinetic energy of the tram into electrical energy. This electrical energy is then fed back to the overhead line or dissipated in brake resistors. A microprocessor-controlled switching system, known as a *chopper,* controls this process. The electrodynamic brake becomes less effective at low vehicle speeds.
- A pneumatic brake which uses air-operated disc brakes fitted to the vehicle axles.
- A magnetic track brake which uses electro-magnets to clamp brake shoes directly to the rail head (figure 6). These brakes are only utilised when the driver selects either the hazard or emergency brake (see paragraph 39).

33 The trams are provided with a sanding system which uses compressed air to blow sand onto the rail head just ahead of the wheels. The purpose of the sand is to increase the available adhesion at the wheel/rail interface. The sand system can be operated by the driver (using a button on the cab desk), or it can be operated automatically by:

- the wheel slide protection system (see paragraphs 34 to 38);
- deployment of the hazard brake (see paragraph 39); and
- deployment of the emergency brake (see paragraph 39).

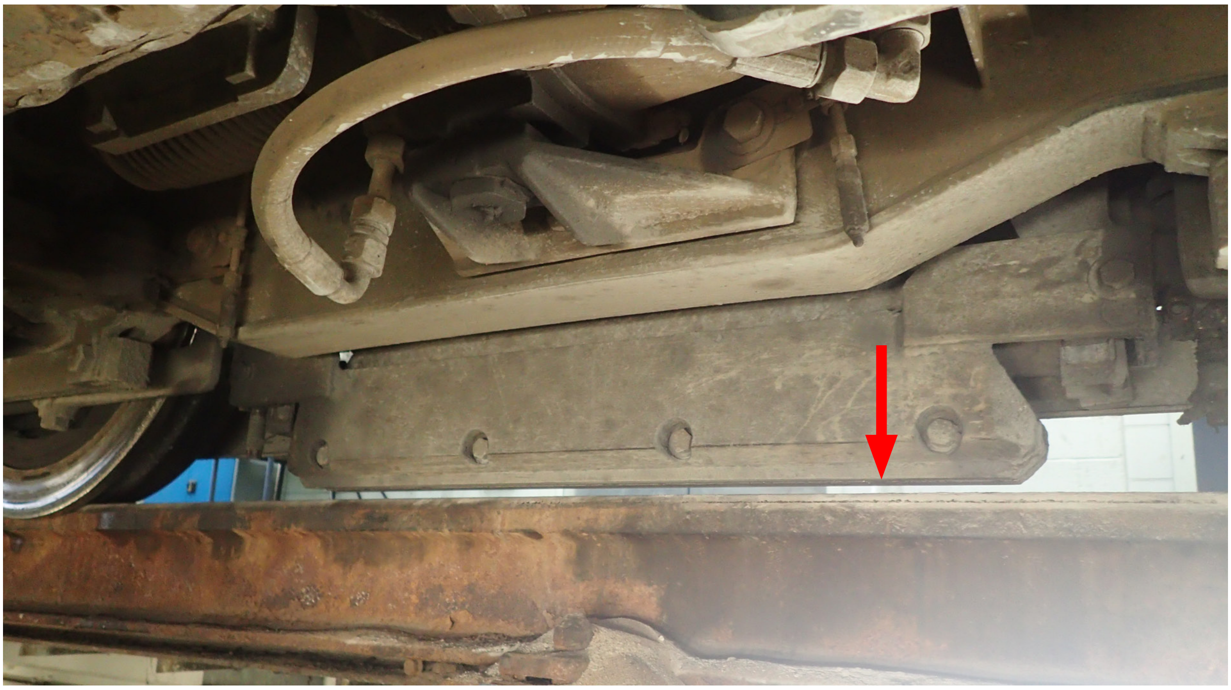

Figure 6: A magnetic track brake shoe as fitted to a Sheffield tram; arrow indicates direction of movement of magnetic track brake when energised

Wheel slide protection system

34 The maximum achievable braking force between the tram wheels and the rail is dependent on the level of adhesion (friction) between them. The level of adhesion is normally expressed as a coefficient of friction (symbol 'μ'). The lower the value of μ, the lower the adhesion between wheel and rail and the more likely that the wheel will slide under braking, rather than continuing to rotate. A typical value of μ for contact between a dry wheel and rail is around 0.20. This can fall to around 0.10 during wet weather. Low adhesion conditions are said to exist when μ falls below 0.10. In extreme cases, μ can fall as low as 0.01[1].

35 To assist with braking in low adhesion conditions, each tram is fitted with a *Wheel Slide* Protection (WSP) system. The WSP system (equivalent to anti-lock brakes on a conventional road vehicle) ensures that the braking system makes optimum use of the available adhesion, and also prevents damage to tram wheels and the rails caused by sliding.

36 The WSP system uses probes fitted to the tram axles which provide a signal proportional to the rotational speed of each axle. These signals are then evaluated using a microprocessor-based algorithm which determines whether one or more axles are rotating slower than other axles on the vehicle, or if the deceleration rate of one or more axles is greater than a pre-defined deceleration rate.

37 Either one of these conditions indicates that one or more axles is sliding. Wheel slide occurs when the braking force applied between the wheel and the rail is greater than the available adhesion can accommodate. In the event that wheel slide is detected, then the WSP system will immediately reduce the braking force to a level which can be achieved without sliding. On the Sheffield trams, detection of wheel slide also triggers an automatic operation of the vehicle sanders.

[1] See RAIB report 26/2014, Buffer stop collision at Chester station 20 November 2013, paragraph 89.

38 The WSP system also acts to limit *wheel slip* (spin) when the tram is accelerating under power.

Control of the braking systems

39 The driver of a Sheffield tram has three ways in which to apply the brakes (figure 7):

- In normal operation, the driver will use service braking. This is controlled by a combined power/brake controller located on the cab desk. Service braking uses only the electrodynamic brake for speeds greater than 7.5 mph (12 km/h). Below this speed, the electrodynamic brake becomes ineffective, and therefore the pneumatic brake is also applied. The blending of the pneumatic brake with the electrodynamic brake is fully automatic; no action is required by the driver.
- In the event that the driver needs to rapidly brake the tram, he has the option to use the hazard brake. Use of the hazard brake applies the electrodynamic brake, makes a full application of the pneumatic brake, and also deploys the magnetic track brake. Sanding will also take place. The hazard brake operation is commanded from the same power/brake controller (figure 7) as the service brake by the driver moving the controller backwards through a *detent*.
- The driver also has the option to use the emergency brake. This is initiated by pressing an emergency plunger located on the driver's desk in the cab (figure 7). The emergency brake commands the operation of the electrodynamic, pneumatic and magnetic track brakes, and also operates the sanding system. The emergency brake function is independent of the microprocessor system controlling the tram and is provided to mitigate the risk of a failure of the microprocessor system.

40 In the circumstances of the accident at Shalesmoor, application of the hazard brake (paragraph 45) would have had the same braking effect as application of the emergency brake.

Figure 7: Layout of cab controls

Identification of the immediate cause

41 **Tram 120 was unable to stop before colliding with stationary tram 118 on the same line.**

Identification of causal and underlying factors

42 The accident occurred due to a combination of the following causal factors:

a. The driver of tram 120 did not drive the tram in a manner appropriate for the conditions.

b. The brakes on tram 120 did not provide the level of braking expected by the driver. The management of low rail head adhesion by Stagecoach Supertram, being non-compliant with its own procedures, underlies this.

c. Tram 118 had remained stationary in Shalesmoor tram stop.

Each of these factors is now considered in turn.

43 **The driver of tram 120 did not drive the tram in a manner appropriate for the conditions.**

The driving of the tram

44 As the driver of tram 120 proceeded towards Hillsborough from Malin Bridge, he encountered a 'stop' indication from the traffic signal system. This indicated to him that another tram had approached Hillsborough from the Middlewood route, and was a short distance in front. However, tram 118 had departed from Hillsborough tram stop by the time that tram 120 arrived. Tram 120 proceeded towards Shalesmoor, stopping at all three intermediate tram stops. Tram 118 was occasionally visible in the distance. Tram 120 had commenced braking for the tram stop at Shalesmoor from a speed of 23 mph (37 km/h) approximately 230 metres before the point of collision. The tram was still moving at 22 mph (25 km/h) when it passed the 20 mph (32 km/h) speed limit board near St Phillips's Road (paragraph 6 and figure 8). Thereafter, stationary tram 118 would have become visible to the driver of tram 120 approximately 70 metres before the collision (figure 8). Tram 120 was travelling at 18 mph (29 km/h) at the 15 mph (24 km/h) limit (paragraph 6 and figure 8) on the final approach to Shalesmoor tram stop.

45 The data recorder on tram 120 showed that the driver deployed the hazard brake 25 metres before the collision, when the tram speed was 14 mph (23 km/h). Had there been normal levels of rail head adhesion, this distance should have been sufficient for tram 120 to stop before colliding with tram 118. However, the low level of rail head adhesion present at Shalesmoor (paragraphs 55 to 58) meant that the hazard brake was significantly less effective than would normally be expected.

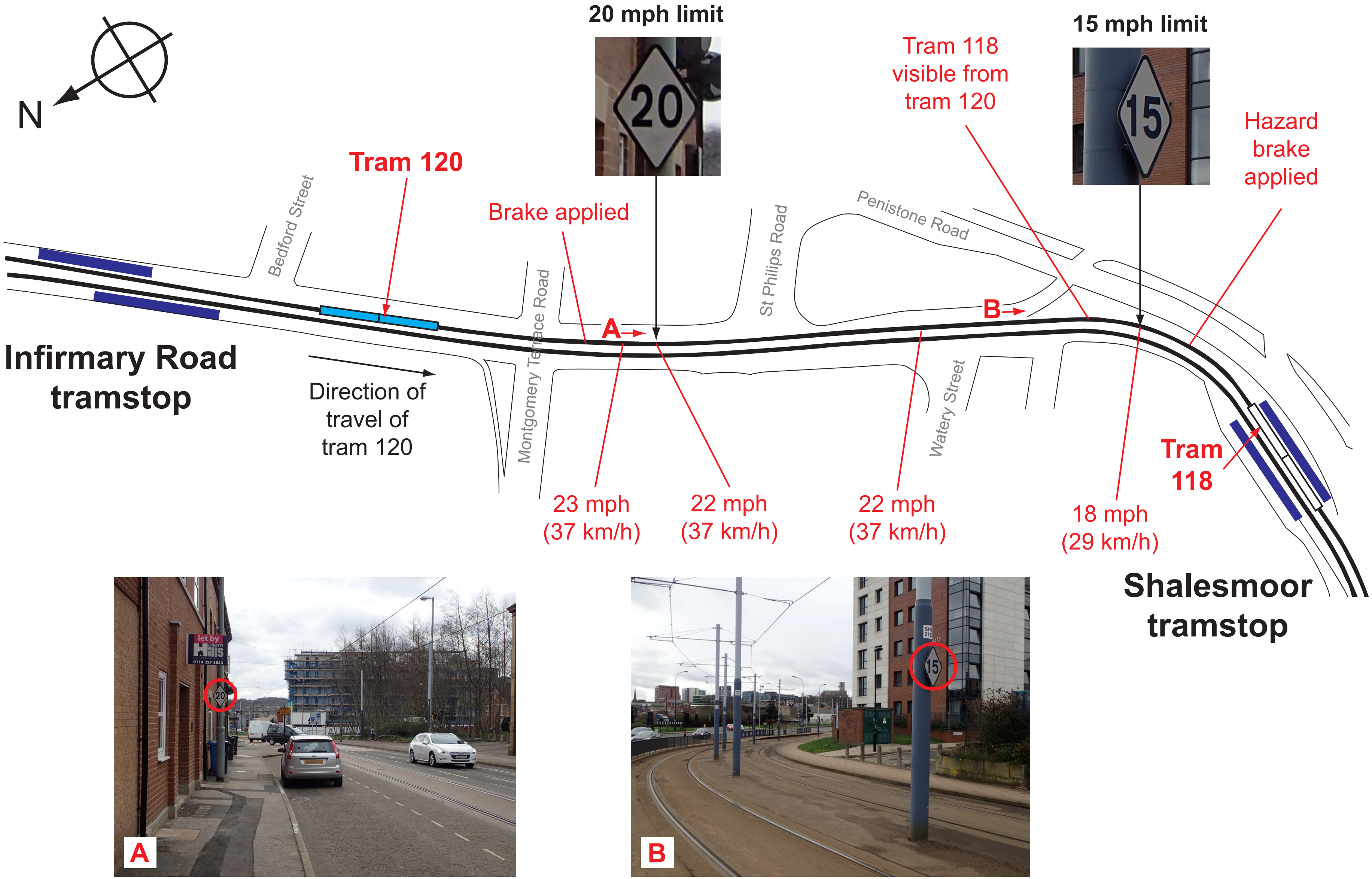

Figure 8: Map showing start of braking, 20 and 15 mph signs, point of deployment of hazard brake and point of impact

46 The RAIB carried out an analysis of tram speeds between Hillsborough and Shalesmoor on the morning of 22 October 2015 before the accident using data from the VIS loop system for four sections of the route. The sections were chosen to minimise, as far as possible, the effect of traffic lights and road congestion. The average speed for each of seven trams on each of the four sections was calculated. This data is shown in figure 9. Tram 120 recorded the highest average speed on two of the four sections, and was above the median for the other two sections.

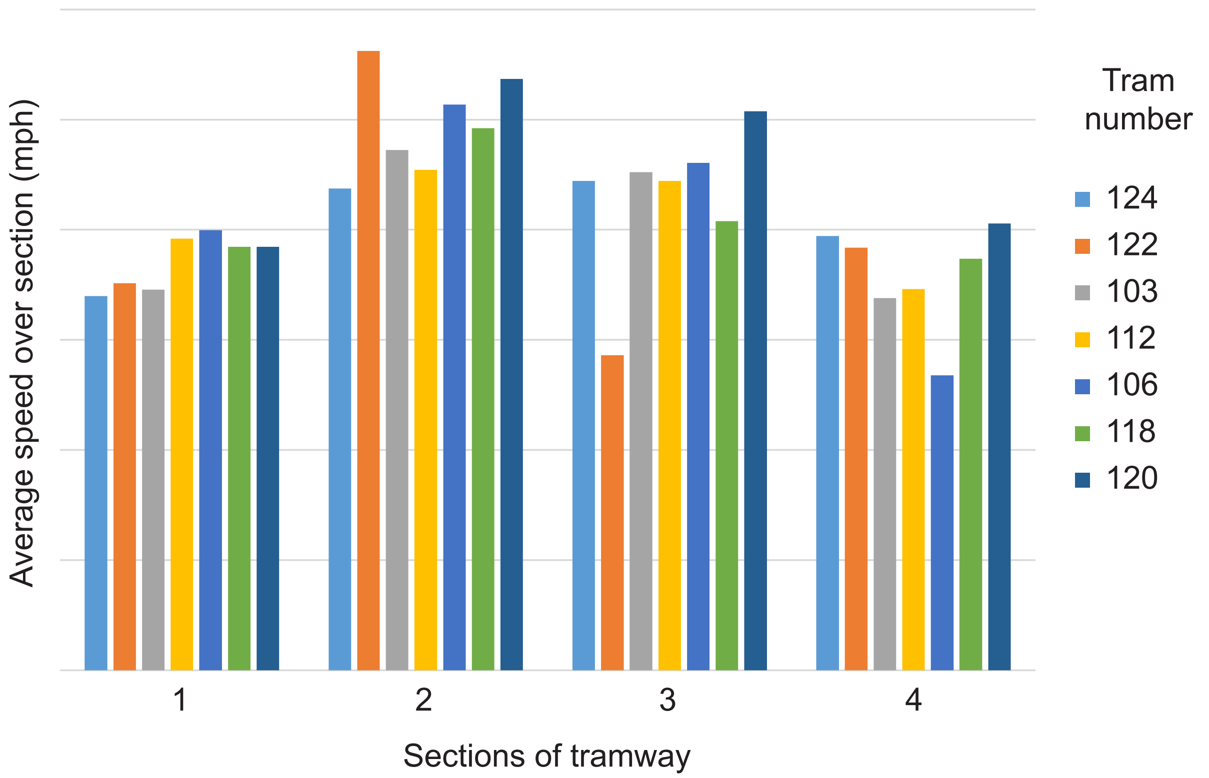

Figure 9: Comparison of average speeds (mph) of seven trams on four sections of track between Hillsborough and Shalesmoor on 22 October 2015

47 Using evidence from the On-Tram Data Recorder (OTDR) and Closed-Circuit Television (CCTV) systems fitted to trams 118 and 120, the RAIB compared the speed profile of the two trams on the approach to Shalesmoor tram stop. This data is plotted in figure 10, and indicates that, although the deceleration rates of the two trams are similar (before the application of the hazard brake by tram 120), tram 120 was unable to stop in time because of a combination of its higher initial speed at the 20 mph (32 km/h) speed limit board and the ineffectiveness of the braking systems due to low adhesion conditions.

The driver and his awareness of low adhesion conditions

48 The driver of tram 120 was fully compliant with the driver assessment process operated by Stagecoach Supertram, and held all required competencies. No concerns regarding his driving had been raised by his managers, and he had not been involved in any relevant previous accidents. There was no evidence that the driver management process contributed to the accident.

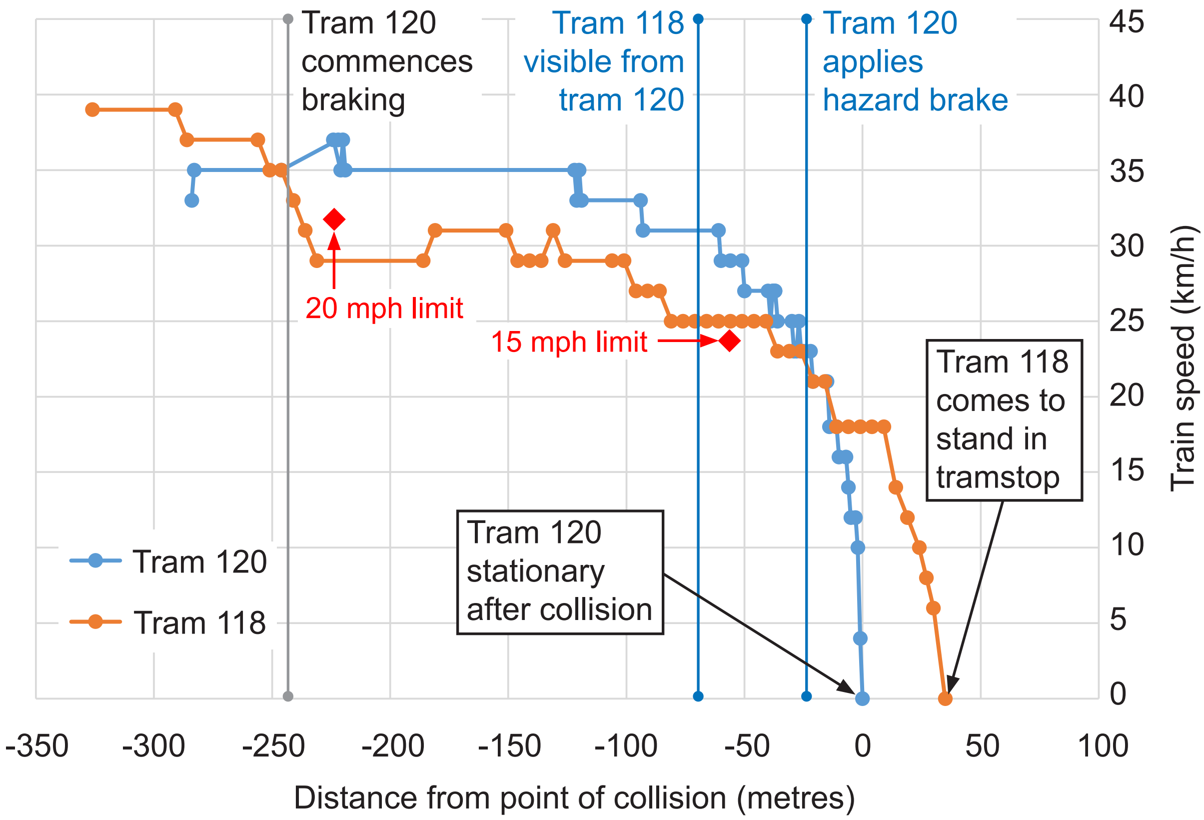

Figure 10: Comparison of speeds of trams 118 and 120 on approach to Shalesmoor tram stop. The point of collision between the trams was approximately one metre before the point at which they came to a final stop. Note that the stopping points are the front of each of the trams. The difference in stopping points is therefore equal to the length of tram 118.

49 As is standard practice, both tram drivers were subject to a Drugs & Alcohol test by Stagecoach Supertram following the collision. Neither driver was found to be under the influence of alcohol or drugs.

50 The RAIB found no evidence to suggest that the driver of tram 120 was fatigued or otherwise distracted from his duties.

51 The driver of tram 120 was experienced (paragraph 14) and he was aware of the hazards created by low rail head adhesion conditions at Shalesmoor. On the morning of 22 October 2015, he had already experienced low adhesion conditions at another tram stop.

52 Stagecoach Supertram was also required by its procedures to ensure and reinforce awareness of low adhesion conditions by the publication of a ‘Winterisation Brief’. Stagecoach Supertram procedure ST0063 Issue 2 rev A required that the Winterisation Brief be issued by 1 October of each year. In 2015, this brief was actually issued on 28 October 2015, after the accident at Shalesmoor. The driver had not therefore been formally reminded to watch out for low adhesion conditions and to modify his driving style accordingly.

53 The brakes on tram 120 did not provide the level of braking expected by the driver due to low adhesion rail head conditions.

The tram's brakes

54 Post-accident testing found no evidence to indicate that there were any defects on tram 120's braking systems at the time of the collision. It had stopped without any problems at previous tram stops before the collision. The correct operation of the magnetic track brakes is confirmed by drivers before trams entering service each morning, and there were no known issues with tram 120 on the day of the collision. Tests carried out with tram 120 following repairs to accident damage showed that the braking systems were functioning as expected.

Rail head contamination

55 The area of Shalesmoor is known to be an area at high risk of rail head contamination in autumn and is identified in Stagecoach Supertram's procedure ST0057 Issue 1 Rev b ('Slip Slide – Cleaning and prevention of contaminated rails'). The primary source of this contamination is from fallen leaves.

56 It is well established[2] in the railway industry that rail head contamination by leaf detritus can lead to a significant loss of adhesion. Such contamination is generally black in colour and is difficult to remove by scraping. Photographs taken immediately after the accident (figure 11) indicate the presence of such contamination. Analysis of rail head swabs taken by the RAIB on 11 November 2015 revealed the presence of organic contamination which appeared similar to that photographed on the day of the accident.

Figure 11: Photograph of rail head at Shalesmoor, taken immediately after accident. Note that rail head is black in colour and the presence of fallen leaves

[2] RAIB Report 25 (Part3)/2006 January 2007, paragraphs 28-32.

57 The effect of the rail head contamination from crushed leaves, combined with the probable presence of moisture from dew, lowered the available adhesion at Shalesmoor. Dew is caused by condensation of atmospheric moisture onto cold surfaces; changing atmospheric humidity around sunrise increases the likelihood of dew forming[3]. Calculations by the RAIB based on OTDR[4] data indicate that the effective coefficient of friction (μ) at Shalesmoor on 22 October 2015 was between 0.05 and 0.04, which represents a very low level of adhesion. However, even lower levels of adhesion have been identified as a factor in previous investigations.

58 The low rail head adhesion on the approach to Shalesmoor tram stop reduced the effectiveness of the braking systems on tram 120. Evidence obtained from the control systems on the tram indicates that the WSP system on the vehicle was operating correctly. It should be noted, however, that as with any vehicle, a WSP system can only optimise the use of the available adhesion and cannot stop a tram more quickly than adhesion levels allow (ie braking distance increases as adhesion levels fall).

Brake testing in low adhesion conditions

59 During the investigation, the RAIB carried out tests to increase its understanding of the performance of the tram brakes and associated systems in low adhesion conditions. Tests were carried out by making measured stops from a speed of 12 mph (20 km/h) within the Supertram depot at Nunnery (figure 12). The testing speed was limited for safety reasons by the available length of track. Stops were made using the service brake and the hazard brake in both normal dry rail head conditions and in low adhesion conditions.

60 Low adhesion conditions were created by applying moistened paper tape to the rail head and rolling it onto the surface while spraying water. The paper tape was then run over by multiple passes of a tram. This method of artificially creating low rail head adhesion conditions has been used extensively in the railway industry to generate low adhesion conditions for brake testing and driver training. The paper tape was prone to being scrubbed from the rail head by the tram's magnetic track brakes, and therefore multiple applications of the tape was required to consistently maintain low rail head adhesion conditions. It should be noted that the leaf contamination at Shalesmoor (paragraph 56) is unlikely to have been so easily scrubbed from the rail head by the magnetic track brakes.

61 In the tests the stopping distance was found to increase from around 12 metres on dry uncontaminated rail to around 35 metres in the simulated low adhesion conditions, when using the full service brake. When the hazard brake was used (and sanding was automatically activated), the braking distance was found to increase from around 8 metres to around 19 metres.

[3] RAIB Report 25 (Part3)/2006 January 2007, paragraph 69.

[4] The OTDR data used was obtained from tram 118; this tram had slid for the last two metres when coming to a stand in Shalesmoor tram stop, indicating that it was braking at the limit of the available adhesion.

62 The tests confirmed that braking distances in low adhesion conditions, using both the service brake and the hazard brake, are significantly extended compared to normal dry rail conditions. The tests also confirmed that magnetic track brakes are adversely affected by a low coefficient of friction between the magnetic track brake shoe and the rail head[5].

Figure 12: Testing in simulated low adhesion conditions at Nunnery Depot . The tram is moving towards the viewer. Paper tape has been applied to the railhead from the crossing onwards

63 It was reported that at the time of the collision the tramway infrastructure around Shalesmoor was heavily contaminated with sand, probably deposited by other trams working in low adhesion conditions. The possibility that such sand on the rail head might have caused the magnetic track brake to lose its effectiveness was also investigated by depot testing. The tests indicated that sand on the rail head had no adverse effect on the braking performance of the tram when the track brake was deployed, compared to normal dry rail head conditions without any sand.

[5] Note that not all magnetic track brakes are affected by low adhesion in the same way. An alternative design of magnetic track brake, called an eddy current brake, does not rely on friction to achieve the braking effect and is therefore not dependent on rail head adhesion. Eddy current brakes are not generally used on trams.

64 The management of low rail head adhesion by Stagecoach Supertram was not compliant with its own procedures. This was an underlying factor.

Procedures

65 Stagecoach Supertram managed the risk of low adhesion in accordance with procedure ST0057 Issue 1 Rev b 'Slip Slide – Cleaning and Prevention of Contaminated Rail'. This procedure contained both proactive and reactive measures to reduce the risk from low adhesion conditions.

66 The proactive elements of ST0057 required the Stagecoach Supertram facilities team to monitor defined high risk areas for leaf fall. Shalesmoor was one of these defined high risk areas. Records indicate that the facilities team had visited Shalesmoor on 22 October 2015 and had blown fallen leaves away from the tramway (paragraph 18).

67 The reactive elements of ST0057 required that:

- tram drivers should report to the Operations Control Centre (OCC) if they experienced wheel slide, caused by low adhesion;
- the OCC should log such reports, and advise the facilities team; and
- the facilities team should visit the reported location, and treat the railhead using a *traffic film remover* (TFR) product.

Driver reporting and OCC action

68 Tram drivers can become aware of low rail head adhesion in a number of ways. These include:

- Reports from other drivers and/or the OCC.
- Sensing low deceleration or extended stopping distances.
- The audible operation of the sanding system, triggered by the activation of the of the WSP system.
- An indication appearing on the in-cab vehicle status panel, known as the annunciator panel (figure 13). This panel provides information to the tram driver about the status of several different tram systems. Cat A, Cat B and Cat C indicate fault conditions of varying severity, Cat A being the most severe and requiring the vehicle to be withdrawn from service. Cat A, B or C fault indications are normally combined with other indications which assist tram drivers to understand the nature of the vehicle fault. A 'drive' fault is produced by the tram's traction control units (TCUs) and is indicated by an illuminated segment on the annunciator panel. Cat A, B or C illuminated combined with a 'drive' fault illumination is an indicator of repeated wheel slide.

69 Evidence obtained by the RAIB indicates that tram drivers tended to only report low adhesion incidents to the OCC when indications appeared on the annunciator panel. However, the annunciator panel cannot be relied on to indicate all wheel slide events. This is because the software system controlling the annunciator panel uses an internal event counter. Cat A, B, C faults are indicated once the counter has reached set thresholds. However, the counter is reset when the driver changes ends (as happened at Malin Bridge when tram 120 commenced its journey). Following the accident at Shalesmoor, the driver reported that the annunciator panel did not indicate wheel slide on tram 120.

70 A consequence of this dependence on the annunciator panel as the primary indication of low adhesion conditions was that there was a significant under-reporting of low adhesion events by tram drivers to the OCC.

Figure 13: The cab annunciator panel

Non-compliance to procedures

71 The RAIB analysed the OCC low adhesion report log (paragraph 67), and compared this to the work records produced by the facilities team. There was little correlation between these records. Furthermore, witness evidence indicated conditions of low adhesion were being experienced by tram drivers but not being recorded in the OCC log. This indicates that the process documented by procedure ST0057 was not being complied with. Sheffield Supertram management did not detect this non-compliance with procedure ST0057.

72 The breakdown in compliance with procedure ST0057 arose primarily because:

- tram drivers were not adequately reporting when they experienced conditions of low adhesion (paragraphs 68 to 70); and
- OCC was not adequately acting on such reports by advising the facilities team, and this led to the poor correlation in the records (paragraph 71).

The RAIB found no evidence that the facilities team were not actioning the reports which were passed to them.

73 The non-issue of the Winterisation Brief before the accident at Shalesmoor (paragraph 52) was also a non-compliance with the procedure.

74 **Tram 118 had remained stationary in Shalesmoor tram stop.**

75 Tram 118 was unable to continue its journey because of queuing road traffic which was occupying a section of the road marked as a box junction (figure 4). The box junction markings are provided to indicate to road vehicle drivers that they must not occupy that section of the road when they cannot proceed further due to queuing traffic at the signalled roundabout. The intent of these markings is therefore to prevent obstruction of the tramway by queuing road vehicles.

76 Rule 174 of The Highway Code states the following:

> 'Box junctions. These have criss-cross yellow lines painted on the road (see 'Road markings'). You **MUST NOT** enter the box until your exit road or lane is clear. However, you may enter the box and wait when you want to turn right, and are only stopped from doing so by oncoming traffic, or by other vehicles waiting to turn right. At signalled roundabouts you **MUST NOT** enter the box unless you can cross over it completely without stopping.'

The road vehicles occupying the box junction and obstructing the path of tram 118 were therefore in violation of the Highway Code.

77 The driver of tram 118 could have used the VIS system to change the traffic lights protecting the tramway/road intersection in front of him to red. However, this would not have had any effect on the road vehicles obstructing the box junction since those road vehicles had already passed the traffic lights which protected the tramway/road intersection (figure 4).

78 Shalesmoor tram stop is used as a timetable timing point. This means that a tram which is running early may have an extended stop at Shalesmoor while it waits for the correct departure time. Therefore, the drivers of following trams should be aware of the possibility of encountering a tram stood at this tram stop. A stationary tram ahead is clearly a normal condition and one which a line-of-sight tramway is designed to accommodate.

Observations

Route risk assessments

79 Stagecoach Supertram undertook routine route risk assessments covering the operation of trams on the routes from Middlewood and Malin Bridge to Shalesmoor in both directions. Although procedure ST0057 Issue 1 rev b defines six locations within these routes (including Shalesmoor) as being at 'high risk' from low adhesion conditions, the RAIB noted that the route risk assessments do not document low adhesion as being a hazard. However, there is no evidence that this oversight was causal to the accident.

Post-incident data download from tram 120

80 The Sheffield trams are more than 20 years old, and the limited functionality of the OTDR reflects the technology of that era. In order to gain a full understanding of the behaviour of the tram following an incident or accident, it is necessary to obtain data downloads from various other systems on the vehicle such as the traction control units and the brake control unit. Following the accident at Shalesmoor, a full download was requested by the RAIB, but the data was not obtained by Stagecoach Supertram. The absence of this data hampered detailed analysis of the performance of the braking system of tram 120.

Procedures for low adhesion management in other light rail systems

81 The RAIB obtained procedures and driver briefings from some other light rail operators covering operations in low rail head adhesion conditions. A review of these indicated a degree of over-reliance on the performance of the magnetic track brakes. The accident at Shalesmoor indicates that the magnetic track brakes are adversely affected by low rail head adhesion (Learning point 1).

Previous occurrences of a similar character

82 The RAIB has previously investigated five incidents in which low adhesion rail head conditions were a causal factor. In addition, a bulletin and a class investigation have also dealt with low adhesion-related issues. These incidents are as follows:

- Esher (RAIB report 25/2006 part 1).
- Lewes (RAIB report 25/2006 part 2).
- Autumn Adhesion Class Investigation (RAIB report 25/2006 part 3).
- Darlington (RAIB bulletin 01/2010).
- Exeter St David’s (RAIB report 10/2010).
- Stonegate (RAIB report 18/2011).
- Chester (RAIB report 26/2014).

All of the above incidents and accidents involved heavy rail vehicles and are not directly relevant to the circumstances of this accident.

Summary of conclusions

Immediate cause

83 Tram 120 was unable to stop before colliding with stationary tram 118 on the same line (**paragraph 41**).

Causal factors

84 The causal factors were:

a. the driver of tram 120 did not drive the tram in a manner appropriate for the conditions (**paragraph 43**);

b. the brakes on tram 120 did not provide the level of braking expected by the driver due to low adhesion rail head conditions (**paragraph 53, Recommendation 1**); and

c. tram 118 had remained stationary in Shalesmoor tram stop (**paragraph 74**).

Underlying Factor

85 The management of low rail head adhesion by Stagecoach Supertram was not compliant with its own procedures (**paragraph 64**).

Observations

86 Although not linked to the causes of the accident, the RAIB observed that:

a. Stagecoach Supertram route risk assessments did not include low adhesion as a hazard (paragraph 79).

b. A full data download from tram 120 was not taken after the accident (paragraph 80).

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

87 Stagecoach Supertram is in the process of revising its processes for the management of low rail head adhesion conditions. Specific measures being taken include:

- Obtaining detailed weather predictions to indicate the likelihood of low rail head adhesion conditions. These predictions will be disseminated to tram drivers and to the facilities team.
- Carrying out pre-emptive applications of traffic film remover to the rail head in areas known to be at risk of low adhesion.
- Additional resources within the facilities team.
- Amending the relevant section of the tramway rulebook to clarify that drivers must not rely solely on the in-cab annunciator panel to indicate when occurrences of low adhesion must be reported to the OCC.
- Ensuring that the OCC staff are made aware of the importance of passing driver’s reports onto the facilities team.

The intention of Stagecoach Supertram is that these measures will be fully implemented by autumn 2016.

Recommendation and learning point

Recommendation

88 The following recommendation is made[6]:

1 *The intent of this recommendation is that operators of light rail systems actively review and recognise any risks on their systems arising from low adhesion conditions, and proactively manage these risks. The RAIB has reviewed procedures for the management of low adhesion from a number of UK light rail systems, and believes that the safety learning from the accident at Shalesmoor could be applied to these other systems.*

UK tram operators should review their processes for assessing and managing the risk from low adhesion conditions on their networks. This should include consideration of how drivers are trained and briefed for the low adhesion season, and other measures to manage low adhesion conditions. Where this review shows it to be necessary, operators should put in place a timely programme of improvements.

[6] Those identified in the recommendation, have a general and ongoing obligation to comply with health and safety legislation and need to take this recommendation 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, this recommendation is addressed to the Office of Rail and Road to enable it to carry out its duties under regulation 12(2) to:

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

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

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

Learning point

89 The RAIB has identified the following key learning point[7]:

1 This accident demonstrates that the performance of friction-type magnetic track brakes can be adversely affected by rail head contamination in a similar way to the friction brakes on the wheels. Tram drivers should therefore adopt a defensive driving style in low adhesion conditions that does not place undue emphasis on the added braking effort provided by the track brakes.

[7] ‘Learning points’ are intended to disseminate safety learning that is not covered by a recommendation. They are included in a report when the RAIB wishes to reinforce the importance of compliance with existing safety arrangements (where the RAIB has not identified management issues that justify a recommendation) and the consequences of failing to do so. They also record good practice and actions already taken by industry bodies that may have a wider application.

Appendices

Appendix A - Glossary of abbreviations and acronyms

CCTV	Closed-circuit Television
OCC	Operations Control Centre
OTDR	On-Tram Data Recorder
TFR	Traffic Film Remover
VIS	Vehicle Identification System
WSP	Wheel Slide Protection
μ	Co-efficient of Friction

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.

Chopper	A means of controlling the speed of traction motors by turning the electrical supply rapidly on and off.*
Detent	A mechanical device fitted to the brake controller which prevents inadvertent movement of the controller from the service brake into the emergency position.
Dwell time	The time a tram uses in stopping at a tram stop.*
Electrodynamic braking	A system of braking where the retardation effort is provided by using the traction motors to generate electricity.
Grooved Rail	A type of flat bottom rail that has an integral check rail, giving it a section similar to a wine glass. They are generally used where the track is to be built as part of a highway, as it simplifies construction.*
Inbound	On the Sheffield Supertram network, this refers to a tram journey travelling towards Sheffield city centre.
Line-of-sight	A method of working trains or trams in which the driver observes the line beyond and controls the speed of the train or tram appropriately. Often employed by tramway systems in street running areas, where speeds are lower.*
Median Strip	The area of land between the two carriageways of a dual-carriageway road.
Standard Gauge	1435 mm between the inside running edges of the rails.
Traffic Film Remover	A product used by Stagecoach Supertram to remove contamination from rail heads.
Wheel Slide	Wheel slide occurs when a wheelset ceases to rotate when a brake force applied to the wheelset exceeds the available adhesion between the wheelset and the rail head.
Wheel Slip	Wheel slip occurs when the traction force applied to a wheelset exceeds the available adhesion between the wheelset and the rail head.

Appendix C - Investigation details

The RAIB used the following sources of evidence in this investigation:

- information provided by witnesses;
- information taken from the tram's on-tram data recorder (OTDR);
- closed circuit television (CCTV) recordings taken from trams 118 and 120;
- site photographs and measurements;
- meetings with Stagecoach Supertram staff;
- discussions with Siemens staff;
- weather reports and observations at the site;
- testing of trams; and
- a review of previous RAIB investigations that had relevance to this accident.

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Any enquiries about this publication should be sent to:

RAIB
The Wharf
Stores Road
Derby UK
DE21 4BA

Telephone: 01332 253300
Fax: 01332 253301
Email: enquiries@raib.gov.uk
Website: www.gov.uk/raib