HSE
Health & Safety Executive

The train collision at Ladbroke Grove 5 October 1999

A *report of the* HSE *investigation*

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Contents

1. FOREWORD

1.1 On 5 October 1999, at 8.09am, a Thames Trains 3-car turbo class 165 diesel unit (the "165" for the purposes of this report) travelling from Paddington to Bedwyn, in Wiltshire collided with a First Great Western High Speed Train (the "HST") travelling from Cheltenham Spa to Paddington. The collision took place at Ladbroke Grove Junction, 2 miles outside Paddington station. As a result of the collision and the subsequent fires, 31 people died (24 from the 165 and 7 from the HST, including the drivers of both trains) and a further 227 were taken to hospital. 296 people were treated for minor injuries on site.

1.2 Following this incident the Health and Safety Commission (HSC) immediately requested the Health and Safety Executive (HSE) to conduct an investigation and report under section 14(2)(a) of the Health and Safety at Work etc. Act 1974 (HSW Act). HSC also subsequently announced that Lord Cullen would conduct a public inquiry under Section 14(2)(b) of the HSW Act, with the following terms of reference:

> "1. To inquire into, and draw lessons from, the accident near Paddington station on 5 October 1999, taking into account the findings of the HSE's investigations into immediate causes.
>
> 2. To consider general experience derived from relevant accidents on the railway since the Hidden Inquiry, with a view to drawing conclusions about:
>
> (a) factors which affect safety management
>
> (b) the appropriateness of the current regulatory regime
>
> 3. In the light of the above, to make recommendations for improving safety on the future railway."

1.3 Prior to this report, HSE published three interim reports of their investigation, on 8 October 1999, 29 October 1999 and 14 April 2000. These reports were submitted as part of HSE's evidence to the Ladbroke Grove Rail Inquiry (LGRI). This final report consolidates that information together with the results of further investigations which were only completed in September 2000. **Given the terms of reference for Lord Cullen's inquiry, this HSE report is factual and does not make recommendations. It concentrates primarily on technical issues surrounding the causes of the collision rather than root causes. It also records the immediate actions taken after the collision.**

2. EXECUTIVE SUMMARY

2.1 The collision was initially caused by the 165 passing a red signal, signal SN109, at Ladbroke Grove. The 165 continued for some 700 metres into the path of the HST, and the closing speed of the two trains was in the region of 130 mph.

2.2 Signal SN109 had been a signal passed at danger (SPAD) seven other times over the preceding five years, and was one of the top 22 most SPADed signals on the Railtrack network.

2.3 The investigation identified a number of significant factors whereby the signalling in the Paddington area did not comply with relevant industry standards, with the overall conclusion of signal sighting experts being that the signal viewing conditions presented an exceptionally difficult signal reading task.

2.4 The reasons why the 165 passed the red light are complex. There were no indications that the driver, Mr. Michael Hodder, deliberately set out to pass signal SN109 at red, and the investigation concluded that any acts or omissions by him were just one group of contributory factors.

2.5 Mr. Hodder was not an experienced driver, having only qualified as a driver 13 days prior to the incident. Thames Trains had sought independent validation of their driver training programme whilst Mr. Hodder was under training, but the various recommendations arising from the consultants' work were not implemented for Mr. Hodder's training programme.

2.6 At the time of the SPAD at signal SN109 train movements in the Paddington area were being controlled automatically. In order to prevent, or mitigate the consequences of, the subsequent collision signallers at the control centre would have had to either send a "stop" radio message or change points within a very short time (around 12-15 seconds) after the SPAD happened. This did not happen.

2.7 Detailed technical examination and tests of the complex critical equipment associated with the signalling system at Ladbroke Grove yielded no evidence that any of the signalling equipment performed otherwise than as expected. Signal SN109 is one of the many signals that is required to be fitted with a train protection system, such as the Train Protection and Warning System (TPWS), by 31 December 2003 by virtue of the Railway Safety Regulations 1999. The collision would have been prevented by properly functioning TPWS.

2.8 No evidence was found that any key safety equipment on the trains, such as braking systems and on-board automatic warning systems, contributed to the collision.

2.9 Damage to various fuel tanks on the trains during the collision caused up to six tonnes of diesel to be released. The catastrophic failure of the leading tank on the 165 caused a cloud of atomised diesel, whose ignition created fireballs both outside the trains and inside the leading coach (Coach H) of the HST. A longer, more sustained fire almost completely burnt out Coach H . A subsequent series of experimental tests showed that whilst it is extremely difficult to obtain sustained burning of HST coach interior materials and components, where significant quantities of diesel are present then fire can be sustained.

2.10 Tests on the doors of both trains revealed no evidence that door locking mechanisms would have impeded egress after the collision. However, damage to doors as a result of the impact, the overturning of some coaches, and passenger communication issues on how to use door release levers and window hammers in emergencies, all created problems. Nevertheless, escape of passengers from the two trains progressed, in the main part, in an atmosphere of calmness and consideration for fellow passengers.

2.11 The aluminium bodied 165 suffered greater damage than the steel bodied HST during the collision, with the front coach of the 165 disintegrating on impact. A programme of work was undertaken to compare the crashworthiness of aluminium and steel bodied rail vehicles of the same generation as those involved at Ladbroke Grove. This work showed that such a comparison is not straightforward, but indicated areas where design improvements, relevant to both types of body shells, could be made.

3. THE INCIDENT

3.1 The simplified diagram of the layout of the lines in the Ladbroke Grove area at the time of the collision is at **Appendix 1** .

To the *west* of Ladbroke Grove Junction there are four running lines:

- the Up and Down Main lines and
- the Up and Down Relief lines.

The "Up" direction of travel is towards Paddington.

To the *east* of Ladbroke Grove Junction there are six bi-directional running lines identified as Lines 1 to 6. At the junction there are connections between the various lines. Access from Line 3 to either the Down Main or Down Relief lines, for trains travelling towards Reading, is controlled by signal SN109. This signal is located on a gantry which spans the six lines and carries signals for the other lines (except Line 1).

3.2 The signalling in the Paddington area is controlled by a Solid State Interlocking (SSI) system located at the Slough Control Centre (the IECC). The system also includes a computer-driven Automatic Route Setting (ARS) facility. ARS requests the SSI to set routes for trains in accordance with a pre-loaded timetable, instead of the signaller doing it manually. The sequence of events leading up to the collision on the 5 October has been deduced from an analysis of the SSI and IECC data tapes, information from the on-train data recorders on the 165 (the "black boxes"), witness statements and post incident examination.

3.3 On 5 October 1999, the 06.03 Cheltenham to Paddington HST train (train 1A09) was following an earlier train along the Up Main line towards Paddington. As the previous train passed the signals they turned to red and then progressively changed back through yellow to double yellow and then green as the train proceeded - which is normal. Therefore, the HST (some distance behind the earlier train) was travelling on green signals.

3.5 The ARS had set a route for the 08.06 Paddington to Bedwyn 165 train (train 1K20) to signal SN109 on Line 3. On leaving Paddington Station the 165 had travelled via signals SN 43, 63 and 87 on Line 4 and crossed over to Line 3 on the approach to signal SN109. As the 165 approached signals SN 87 (at single yellow) on gantry 6 and SN109 (at red) on gantry 8 all other signals on these gantries were displaying red.

3.6 Immediately before the collision, the signaller who had been monitoring the progress of the trains on a visual display unit (VDU) panel in the IECC realised (from an audible alarm and a visual display indicating a track circuit being occupied by a train "out of sequence") that the 165 train had passed signal SN109 at red and was heading towards the Up Main Line on which the HST was approaching. As a result he changed signal SN120 on the Up Main Line to Danger. A colleague working at the other workstation near by, who realised that a "signal passed at danger" (SPAD) had occurred, stated that he initiated a STOP message to be broadcast to the driver of the 165 by cab secure radio. However, by the time this occurred the HST was very close to the signal SN120 and the collision occurred almost simultaneously. At the speed that the 165 was travelling, it would have taken about 30 seconds after passing signal SN109 before it reached the point of collision (Chapter 10 gives more details on these signaller issues).

3.7 Examination of the SSI data tape confirmed that the route for the HST had been requested by the ARS, and that the instructions were processed by the SSI. It also confirmed that the commands had been issued to the computer modules which controlled the signals and points for a route from the Up Main Line to Line 2 and Paddington Station. The signal aspects displayed for the HST, and its progress through the relevant track circuits, were recorded on the data tapes. The data tapes also show that the ARS requested the route to signal SN109 for the 165 train. The tapes show that no route was set from signal SN109 and that the 165 passed it when it was showing a red aspect. The data tapes then identify the progressive occupation of track circuits as the 165 passed signal SN109 and show it travelling some 700 metres into the path of the HST.

3.8 The point of collision was around 3173 metres from Paddington. At impact, the 165 was travelling marginally under 50 mph and the HST in the range 81-84 mph (although this may have been reduced slightly due to braking), giving a closing speed in the region of 130 mph. The impact was virtually head-on, with the offset of the centre lines of the two trains when they collided only being in the region of 0.3-0.4 metres. The diagram at **Appendix 2** shows where the trains eventually came to rest and the coach identification numbers used subsequently in this report.

3.9 The investigation into the mechanics of the collision suggested that the initial impact was between the HST leading power car drawgear/ headstock and the front coupler of the leading 165 coach, Coach B3. The cabs of Coach B3 and the HST leading power car were destroyed. The HST continued to penetrate Coach B3, which rapidly started to break up. During this initial catastrophic phase the fuel tank under Coach B3 was ruptured and disintegrated (probably due to the rapid detachment and reversal of Coach B3's leading bogie), spreading its diesel contents in a highly atomised cloud, which then ignited into a fireball. A section of the floor from Coach B3 embedded itself in the smaller of the two HST fuel tanks.

3.10 At about the same time as the main collision there were secondary collisions involving other carriages within each train. As Coach B3 was driven backwards by the much heavier HST, it impacted with the leading end of the middle 165 coach, Coach B2. The leading end of the first HST coach, Coach H, also impacted with the trailing end of the HST power car, which then veered off to the right. Coach H started to rotate as it followed the HST power car, and jack-knifed as it was pushed round by the other HST coaches following through, with Coaches F and G toppling over. A subsequent impact between an HST coach and the trailing 165 coach,

Coach B1, caused the latter to topple over. When the vehicles came to a halt, the leading power car of the HST had travelled approximately 90 metres from the point of collision, with the HST trailing power car and Coaches A-G travelling approximately 170 metres before coming to rest (see diagram at Appendix 2 for details).

3.11 The 165 Coach B3 disintegrated in the impact, with structural fractures occurring along weld lines in the aluminium structure, and its debris was scattered over 130 metres. The structures of the HST coaches, in contrast, stood up well to the collision. However, a fire developed and grew quickly in Coach H, and within a few minutes had rapidly escalated throughout the whole coach. This was subsequently almost completely burnt out.

3.12 As a result of the collision and the fires, 31 people died (24 from the 165 and 7 from the HST) and a further 227 taken to hospital. 296 people were treated for minor injuries on site.

4. THE INVESTIGATION

4.1 A member of the public was the first to inform HSE about the collision, within 10 minutes of it occurring. An hour later four inspectors from HSE's Railway Inspectorate (HMRI) were on site.

4.2 Immediate site liaison was established with key railway industry representatives and the emergency services, who were still fully involved in the rescue phase of the operation. In particular, early discussions were held with British Transport Police (BTP) to implement the work-related deaths protocol which HSE has with Police Forces and the Crown Prosecution Service (CPS). This protocol acknowledges that in the case of a work-related death on the railway HSE and BTP both have different, but closely linked, roles and responsibilities. BTP has responsibility to investigate crime in general, and particularly the possibility of manslaughter or corporate manslaughter charges in the case of deaths, and also have a role in assisting the coroner. HSE, on the other hand, is the national statutory body responsible for enforcement of health and safety legislation, but cannot investigate or prosecute for general criminal offences such as manslaughter. In accordance with the protocol, the Ladbroke Grove Investigation therefore became a joint investigation, with HSE conducting the investigation into technical issues (including why the accident happened and what remedial action needed to be taken), whilst BTP conducted the part of the investigation which explored potential manslaughter or corporate manslaughter issues[1]. Throughout the investigation there was excellent co-operation and liaison between HSE and BTP.

4.3 HSE maintained a site investigation team at Ladbroke Grove for the 9 days of the on-site investigation. In addition to its Railway Inspectors, HSE called on the services of a wide range of its staff, including other health and safety inspectors, construction specialists, administrative staff, and photographic, fire and mechanical engineering experts from its Health and Safety Laboratory (HSL). In addition, consultants W S Atkins Rail Limited and AEA Technology Rail (part of AEA Technology plc) were contracted to provide other specialist advice. W S Atkins staff concentrated on the on-site examination of signalling related equipment and rolling stock issues, whereas AEA was primarily to identify the point of impact, map debris and damage, and look at track related items.

4.4 The on-site investigation phase involved painstaking and difficult searches of the debris which was spread over a distance of some 119 metres. Eventually all the damaged rolling stock and debris were transported to secure storage facilities within the Adtranz depot in Crewe for further examination. Key items of signalling and other trackside equipment were also removed for further examination and tests.

4.5 The subsequent off-site HSE investigation into technical issues involved HSL and W S Atkins and aimed at answering the following:

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[1] The workplace death protocol accepts that when the police/CPS decide that a charge of manslaughter or any other serious offence cannot be justified, HSE will continue with its own investigation in relation to breaches of health and safety legislation.

a) Was the safety critical equipment associated with both the signalling system and the two trains working correctly at the time of the collision? (Chapters 5 & 6)

b) What had been done to prevent the SPAD at signal SN109 and, once the SPAD had occurred, to mitigate its consequences? (Chapters 7, 8, 9 & 10)

c) What were the causes of the various fires which occurred after the collision? (Chapter 11)

d) How were passengers able to escape from the two trains immediately after the collision? (Chapter 12)

e) What were the reasons for the differences in damage to the aluminium bodied 165 compared to the steel bodied coaches of the HST? (Chapter 13)

f) What immediate remedial action needed to be taken to prevent a further collision? (Chapter 14)

This technical investigation led to the production of over 60 detailed technical reports by Atkins and HSL (see list at **Appendix 3**). The results of these are summarised in the relevant Chapters of this report.

4.6 The public interest/concern over the collision was intense, and in view of this HSE decided that there was an overwhelming public interest in making the facts of the collision known as quickly as possible. A first interim report was published three days after the collision, summarising the findings from the first 48 hours of the on-site investigation, with a second interim report some three weeks later. Throughout the investigation the key parties received copies of the detailed HSL/Atkins/AEA reports, and all parties to the Ladbroke Grove Rail Inquiry (LGRI) also received copies of those reports as part of HSE's evidence to the Inquiry. As the technical investigation had not been fully completed by the time of the opening of the Inquiry, a third interim report was published on 14 April to provide a summary of the investigation to date. As it became available detailed evidence from HSE's technical investigation was submitted to LGRI throughout the hearings. This final HSE report updates the third interim report and provides a consolidated record of the technical investigation.

4.7 Investigations by BTP into possible manslaughter implications of the collision continued in parallel with the HSE technical investigation and were closely coordinated with it. BTP took over 3000 statements from passengers, witnesses, railway employees etc., and obtained and analysed around half a million pages of documentary evidence. On the 10 May 2000 BTP/CPS announced that the evidence then available was insufficient to provide a realistic prospect of a conviction for manslaughter. In accordance with the work related death protocol (see paragraph 4.2 above) their papers were then handed over for HSE to consider in relation to potential breaches of health and safety legislation.

5. SIGNALLING ISSUES

5.1 Detailed technical examination and tests of the complex critical equipment associated with the signalling system were carried out by WS Atkins. This included: checks on the SSI Data Design; assessment of the performance of SSI Data Links; testing of relevant signal modules; and assessment of the power supply arrangements. Examination of the fault print out from the IECC revealed that no faults were recorded which could have affected the signaling of the two trains immediately before the collision, and it was established that no maintenance work was being carried out on the signalling equipment at the time. On-site testing of the SSI also revealed no anomalies which could have contributed to the collision.

5.2 Thorough visual inspection and, where appropriate, on-site testing was also carried out of all ancillary trackside signalling components. Although this revealed minor non-compliances with current installation standards and codes of practice (for example, the type of cable ties used inside equipment), none was considered to have any relevance to the behaviour of the signalling system at the time of the collision.

5.3 Where necessary, certain items of signalling equipment were taken from site for laboratory examination and testing. Of particular relevance were the signal heads from SN 63, SN 87, SN 109 and SN 120, which were taken to the W S Atkins Technical Investigation Centre at Crewe for more detailed examination and an assessment of their optical performance.

5.4 No evidence was found to indicate that any of the signalling equipment performed otherwise than as expected. In particular, W S Atkins considered that there could be no doubt that the aspects displayed by signals SN 63, SN 87, SN 109 and SN 120 were in accordance with the commands generated by the SSI trackside modules.

5.5 W S Atkins also carried out an assessment of the design of the original signalling scheme, and reported there were no significant departures from accepted good practice in terms of the signalling principles that applied at the time the scheme was designed and implemented. In their opinion, neither flank nor overrun protection[2] beyond signal SN 109 were specifically required by the signalling principles at the time the scheme was designed. However, had flank and overrun protection beyond signal SN 109 been designed differently it could have influenced, in the circumstances of this collision, the effect of a train passing signal SN 109 at danger.[3]

5.6 Signal sighting issues are considered in Chapter 8.

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[2] Flank protection is protection from overrunning movements approaching on converging tracks, usually by additional controls relating to the setting/ releasing of signals and points.

[3] This issue was considered further at the Ladbroke Grove Rail Inquiry

6. TRAIN EQUIPMENT

Automatic Warning System

6.1 The Automatic Warning System (AWS) consists of trackside permanent magnets, electro-inductors and inductor suppressors which interface with trainborne AWS equipment. The purpose of this equipment is to provide train drivers with audible and visual confirmation of whether an approaching signal is clear (green), at caution (double yellow or single yellow) or at stop (red), and to automatically apply brakes if a caution or stop warning is not acknowledged. This equipment is therefore a critical part of the safety system, and the question whether the 165's AWS was, or was not, operating correctly was particularly crucial given the SPAD at signal SN109 immediately prior to the collision.

6.2 The components of the AWS system recovered from the 165 were extensively damaged and only limited testing of some was possible. However, those components which were capable of being tested were tested at W S Atkins' Technical Investigation Centre and this testing did not identify any reasons which could have caused the AWS to malfunction prior to the collision. In addition, a statement given by the previous driver who drove the train from the same driving cab indicated that at that time the AWS was working normally. Maintenance records indicated that no previous faults with the equipment had been reported.

6.3 The track mounted components of the AWS equipment associated with signal SN 109 were examined and tested by W S Atkins. They did not identify any discrepancies from good practice and specifications which could have contributed to the collision. No irregularities were found in respect of the positioning of the AWS actuating magnet.

6.4 It is known that excessive vibration or shock has the potential to generate incorrect AWS operation, and protection against such vibration/shock was a key issue when the current generation of AWS receivers were being developed. Examination of the track following the collision revealed a track joint with significant mis-alignment between the rails in the vicinity of the AWS magnet for SN 109. It was conceivable, albeit very remotely, that any shock or jolt transmitted to the bogie and thence to the 165's AWS receiver as a result of the bogie passing over that particular joint would have occurred during the critical time necessary to cause a wrong side failure[4]. Such a mal-operation could have caused the driver of the 165 to receive a false 'green signal ahead' indication as he approached signal SN 109. Further work therefore took place to assess the likelihood of whether the train passing over this particular track joint could have caused sufficient vibration of the AWS receiver to cause its mal-operation. This work included assessment of:

- the maximum lateral and vertical accelerations (shock) likely to have been transmitted to the bogie by passage over the rail joint (this was done by using computer modelling based on recordings of vibration

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[4] A wrong side failure is one which results in the protection being reduced or removed

levels on the axle, bogie and AWS receiver which were obtained during normal service running of a similar train to the 165) and

- the magnitude of the accelerations necessary to cause the AWS receiver to respond incorrectly.

This work concluded that the shock produced by the mis-aligned rail joint would not have caused an incorrect operation of the 165's AWS at signal SN109. This was subsequently confirmed by analysis of the data from the 165 data recorder (see paragraph 6.11).

6.5 Although the operation of the HST's AWS was not relevant to the causes of the collision, examination of the HST AWS equipment was carried out for completeness. The receiver unit, mounted on the leading bogie of the power car, had been completely destroyed but the remaining components were subjected to test. The position of the sealed AWS isolation switch confirmed that the AWS would have been in operation, and no faults were found in any of the recovered equipment that could have caused a wrong side failure had the fault been present prior to the collision.

Train data recorders

6.6 Each driving vehicle of a Class 165 is fitted with a Parizzi Memotel data recorder. The purpose of the data recorders is to record essential vehicle information. Functions which are cab specific (such as the AWS bell and horn) are recorded on the leading cab recorder only, whilst functions which are present throughout the train (speed, whether doors are closed etc.) are recorded on both data recorders. The information on the data recorders from the 165 was therefore of vital importance for the investigation.

6.7 The information on the rear data recorder, which was undamaged in the collision, was downloaded on site and provided information on the 165's power settings, brake application and overall speed. However, since it was located in the trailing vehicle, it did not record the AWS functions, or AWS driver responses, on the journey from Paddington.

6.8 The front recorder suffered significant damage in the collision, and it was necessary to take it to the manufacturers, Parizzi, in Italy to download information from the memory module. This was done successfully. Subsequent analysis of that data proved problematical as some of it appeared inconsistent with what should have been "common" data recorded on the undamaged rear recorder. In particular, there were six significant areas of data (which equate to separate parts of the journey) where anomalies were present, and crucially two were on the approach to signal SN109. The data from the front recorder therefore had to be initially viewed with caution.

6.9 This data "corruption" was initially thought to have been the result of the damage sustained by the recorder during the collision. However, correlation between the front and rear recorders for all data outside of the six areas was excellent, and this led to further analysis to resolve the issue. This analysis by W S Atkins identified that two lines of data (the "data address lines") within the memory module for the front data recorder were transposed (this had not been caused by the effect of the collision, but was a fault which had probably been present since the time of the data recorder's manufacture). Normally this would not have mattered, as the transposition would have been corrected automatically when the data recorder's own software was used to download it. However, because of the extensive damage to the data recorder, on this occasion different software had to be used to extract the data, and this software was unable to interpret the rearranged/ transposed blocks of data correctly. Once this problem had been identified, further work was conducted on the raw downloaded data. This ultimately provided effectively 100% correlation between the common data from both the front and rear data recorders, and provided additional information regarding operation of the AWS (see paragraph 6.4).

6.10 Analysis of the information from the data recorders showed that after leaving Platform 9 at Paddington the 165 accelerated, passing signal SN43 (at green) at 38 mph before eventually reaching just over 45 mph on the approach to SN 63 (at double yellow). Power was then reduced, with a short application of the brakes immediately after signal SN63, to bring the speed down to 40mph. The train then coasted, through signal SN87 (at single yellow), for around 750 metres before increasing power to Notch 5 239 metres before signal SN109 (at red) - this was at the point when aspects of all the other signals on Gantry 8 apart from SN109 became fully visible at red. There was a further increase in power to Notch 7 some 107 metres before signal SN109, immediately after Mr. Hodder had cancelled the AWS horn. The 165 passed signal SN 109 at just over 40 mph and continued to accelerate to over 50 mph until less than 100 metres from the collision. There was then a rapid change to braking, with emergency braking just before the collision (this would have been either by selecting emergency braking or by operating the emergency brake pushbutton).

6.11 The front recorder received four inputs from the AWS system during the journey from Paddington:-

- AWS bell circuit energised on approach to SN43 (at green)
- AWS horn, and a record of the driver cancelling it, on approach to SN63 (at double yellow)
- AWS horn, and a record of the driver cancelling it, on approach to SN87 (at single yellow)
- AWS horn, and a record of the driver cancelling it, on approach to SN109 (at red)

No applications of the Driver Reminder Appliance (DRA) were recorded during the journey[5].

[5] The DRA is a device which is required to be set if a train is at a stand before a red signal and it was developed to particularly

Automatic Train Protection

6.12 All First Great Western HST power cars are fitted with automatic train protection (ATP) equipment as part of a pilot scheme started by the British Railways Board in 1989 in response to Sir Anthony Hidden's recommendations following his Inquiry about the train collision at Clapham Junction in 1988.

6.13 At the time of the collision ATP was not functional in the leading cab of the HST. The ATP speedometer had failed on 1 September 1999, repeating an earlier failure, and a standard (non ATP) speedometer had been installed in its place pending a permanent solution to the recurrent fault. As a result ATP was not available to the driver. Examination and testing of the trackborne ATP equipment was therefore carried out to determine whether fully functional ATP had the ability to prevent the collision or reduce its consequences.

6.14 An examination of the ATP loop (a cable which transmits information to an ATP fitted train) on the approach to signal SN120 identified that it was not fixed to the sleepers as it should have been and as a result had become misaligned[6]. This misalignment made it likely that the loop would have been unable to transmit data to an ATP fitted train for over half of its length. Prior to the collision, at the same time as signal SN120 was put back to red by the signaller, an ATP message would have been transmitted by the loop preceding signal SN120 to the train passing over it. Had ATP on the train been operational, this message, although not causing the train brakes to be applied automatically, would have given rise to an audible and visual indication in the cab which could have caused the driver to make an emergency brake application manually. It was not established what section or sections of the loop were sufficiently well aligned to successfully transmit a message but in the context of the collision this is not considered to be relevant as data analysis showed that signal SN 120 was only put back (and therefore the ATP message from the loop transmitted) a few seconds before the collision.

6.15 With the exception of the loop in rear of signal SN120, the performance of all ground based equipment was found to be satisfactorily. However, the ATP system, as installed, would only have applied emergency braking when the HST passed signal SN120 which had been put back to red by the signalman. As signal SN120 is only about 70 metres from the collision point, any automatic braking applied by ATP would not have significantly lessened the speed of impact.

6.16 Although ATP was not operational on the HST at the time of the collision, there was the possibility that the trainborne ATP equipment may have continued to record useful information, such as certain faults in the driver's displays. In view of this the ATP equipment from both the leading and trailing cabs of the HST was examined. Regrettably, the relevant memory chip of the equipment in the leading

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reduce the number of SPADs at platform starting signals. Once the DRA is set, power cannot be applied until it is cancelled, thus providing an additional feature to prevent a driver inadvertently forgetting that the train is stopped in front of a red signal. Further evidence was presented to LGRI that Mr. Hodder had used the DRA during the previous journey into Paddington, and comment on the potential significance of this is left to the report of the Inquiry

[6] Following its discovery, action was taken to reattach the ATP loop to the sleepers before the track was reopened.

cab was too badly damaged for any reliable information to be obtained. The ATP equipment in the rear power car was fully functional, as far as could be ascertained, and had no faults recorded.

6.17 The examination and testing also included the ground based equipment on the approach to signal SN109 to determine if the collision would have been avoided had the 165 been fitted with ATP. No faults were found. Had ATP therefore been fitted to, and operational on, the 165 there would not have been a collision.

6.18 Signal SN109 is one of the many signals that is required to be fitted with a train protection system, such as the Train Protection and Warning System (TPWS), by 31 December 2003 by virtue of the Railway Safety Regulations 1999. The collision would have been prevented by properly functioning TPWS.

Brakes

6.19 Brake and wheel slide protection (WSP) testing on the undamaged rear HST power car and Coaches A-D was completed soon after the collision. Nothing was found which could have fundamentally affected the ability of the HST to stop.

6.20 Brake/WSP testing on Coaches E-H and the leading HST power car was undertaken after they had been transported to the ADtranz depot at Crewe. This work was much more limited because significant parts of the brake/WSP system for the leading half of the HST were severely damaged. However, the tests which were conducted continued to confirm that the braking and WSP systems on the HST were working.

6.21 Brake and WSP testing for the 165 was confined to Coaches B1 and B2. Although some of their brake/WSP equipment was damaged during the collision, tests were able to be carried out and the results were consistent with the correct functioning of the brake and WSP system. Some of the brake and WSP equipment from Coach B3 was located in the wreckage, but was so extensively damaged as to make testing impracticable for that leading vehicle. However, there was no evidence that the brake/WSP system was not working in the leading vehicle. This was later confirmed by evaluation of the data recorder information.

7. DRIVER COMPETENCY ISSUES

7.1 The driver of the 165, Mr. Michael Hodder, was recruited by Thames Trains on 1 February 1999 having previously undergone psychometric testing at a recognised Train Driver Assessment Centre, medical examination and interviews. Following selection, he underwent Thames Trains' driver training programme. This was based on the driver training programme developed by British Rail in the mid 1990s, but modified to meet the company's own requirements. During 1999 Thames Trains had engaged Halcrow Transmark to validate these modifications in their own driver training programme, and the report of this work was produced in May 1999 (whilst Mr. Hodder was in the middle of his training). The report recommended a number of changes in the training programme, including increasing the period of training from 25 to 27 weeks, and reviewing the existing 6 week route learning period, but these were not implemented for Mr. Hodder's training programme[7].

7.2 The British Transport Police (BTP) obtained copies of Mr. Hodder's training records and these were examined by HSE as part of the investigation. The examination showed that he passed the Drivers' Rules Examination on 5 April 1999 and was assessed as competent on the Class 165/166 Thames Turbo following a 'Traction Assessment' on 26 May 1999. Over the following two months he carried out practical handling while accompanied by an instructor. During this time his record shows he made 111 departures from Paddington and successfully stopped 109 times at red danger signals. During his training, Mr. Hodder is recorded as having completed approximately 250 hours of practical accompanied handling, and he was assessed as competent in practical train handling on 15 September. Mr. Hodder's train driver competency certificate was issued on 22 September following formal assessment of his route knowledge during which, however, he was not asked any questions about the Paddington - Ladbroke Grove section of line. Since that date he had completed 9 shifts as the driver in charge.

7.3 An examination of Mr. Hodder's medical records, the results of his performance in aptitude tests and his driver training records did not indicate any reason to doubt his suitability for driver selection at the time of his recruitment by Thames Trains. The eyewitness account from the driver who met Mr. Hodder on the day of the incident contains no reference to his behaviour or attitude as being considered in any way unusual or abnormal. Post mortem tests conducted after the collision confirmed the absence of drugs and alcohol.

7.4 Mr. Hodder was not an experienced driver, having only qualified as a driver 13 days prior to the incident. From documentation relating to his rosters, he had experience of the signalling system and routes for the Paddington area, although the formal assessment of route knowledge (see paragraph 7.2) did not cover the area between Paddington and Ladbroke Grove.

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[7] Subsequently, additional evidence was presented to the Ladbroke Grove Rail Inquiry relating to the quality and content of Mr. Hodder's training and assessment. Comment arising from this is left to the report of the Inquiry.

7.5 An appraisal of Mr. Hodder's rosters, containing details of hours worked and shift patterns for the 17 day period prior to the collision, revealed no grounds for believing that he had been abnormally fatigued from his employment at Thames Trains. It also seems unlikely that Mr. Hodder's apparent failure to react appropriately to the red aspect of signal SN109 could be attributed to the effects of a decline in alertness due to monotony, given that the 165 passed signal SN109 only 3 minutes after leaving Paddington, and Mr. Hodder had had a break of several minutes following completion of his previous journey.

8. SIGNAL SIGHTING

8.1 Extensive examination was carried out by W S Atkins to assess the visibility of signals in the Paddington area, in particular signal SN 109, the signals leading to it (SN63 and SN87), and signal SN120. This work included a number of test train runs for the purposes of signal sighting, as well as observations from track level. The examination also included establishing whether the positioning of the signals, particularly in respect of obstructions to visibility, complied with the provisions of the appropriate railway standards.

8.2 The ability of a train driver to view a signal ahead depends upon a variety of factors, which include line curvature and obstructions such as bridges, overhead line equipment etc. The standards laid down within the railway industry (Railway Group Standard GK/RT0037) require a sighting distance for signals which give a minimum of 7 seconds viewing time at the maximum permitted train speed on the approach to that signal. This standard applies to the whole of the signal, including all aspects and route indicators. The signals passed by the 165 leading up to signal SN109 all had sighting times better than the minimum required. However, the sighting time for signal SN109 was not in compliance with the standard, as although the sighting time for the red aspect of signal SN109 alone did in fact meet the 7 second viewing time, the sighting for the signal as a whole was only 5.9 - 6.4 seconds (depending upon the line of approach) travelling at the maximum permitted speed .

8.3 The view when approaching signals on gantry 8, which includes SN 109, is complex because the signals are frequently partially obscured by the transverse girders below the deck of the preceding Portobello Bridge and by the overhead line equipment. At the time of the collision, all aspects of signals on Gantry 8 were at red, but the red aspect of signal SN109 only becomes fully visible some 60 metres after all the other red aspects are visible.

8.4 The alignment of signal SN 109 is such that at the time of the collision the sun was shining towards it. To determine the effect of sunlight on the visibility of the signal a test train signal sighting run was carried out. This was done on 6 October, the day after the collision, during similar weather conditions and when the sun was in a similar position to that which it had been at the time of the collision. During this signal sighting exercise it was noted that the bright sunlight reduced the perceived brightness of the signal aspect somewhat (by reducing the contrast between the aspect and the immediate surroundings), a phenomenon known as "swamping". However, the lit aspect was readily visible at long range (107 metres). When viewed at close range (17 metres) the lit signal aspect only became identifiable when compared to the unlit aspects, but the degree of swamping of the red aspect was not sufficient to prevent it remaining the dominant aspect as perceived by an experienced observer sitting in a driver's position.

8.5 During the signal sighting run on 6 October 1999 no 'phantom aspects' were detected. This is a known, but rare, phenomenon caused by sunlight being reflected by the internal parts of an unlit signal in such a way that the lens assembly gives the appearance of being lit.

8.6 A summary of information concerning the signals encountered on 5 October 1999 by the drivers involved in the collision is given in the table below:

Signal Number	Applicable to	Description	Aspect displayed to driver	Maximum permissible speed on approach to signal	Sighting time of signal at line Speed
SN 17	Platform 9 (starting signal)	3 aspect, with 2 miniature route indicators	Green	40mph	n/a
SN 43	Line 4	4 aspect, with alpha-numeric route indicator	Green (Route Indicator "4")	40mph	10 seconds
SN 63	Line 4	4 aspect, with junction indicator	Double Yellow (Junction indicator not illuminated)	60mph	12.5 seconds
SN 87	Line 4	4 aspect, with junction indicator	Single Yellow (Junction indicator at position 1)	60mph	17 seconds
SN 109	Line 3	4 aspect, with alpha-numeric route indicator	Red (No Route indication)	60mph (85mph applies 105 metres before signal for moves to the Down Main)	7 seconds (red aspect only) and 5.9 - 6.4 seconds for whole signal (depending on line of approach)
SN 120	Up Main	4 aspect, with junction indicator	Red (Changed by signaller from Green immediately before collision)	100mph	8.8 seconds

8.7 In addition to the colour light aspects, the signals all incorporated some type of junction indicator. For instance, when the signalling system caused signal SN 109 to display any proceed aspect (i.e. green, double yellow or single yellow) it also caused an associated alpha-numeric (fibre-optic type) route indicator to be illuminated. When the signal is at red, though, the junction indicator is not illuminated. Had signal SN 109 been displaying a proceed aspect when the 165 approached, the driver should have expected to see the route indicator illuminated to show either "M", "R" , or "R4" depending upon which route had been set.

8.8 At the time of the Paddington re-signalling scheme, the various British Rail standards/codes which specified parameters for signal installation relevant to signal sighting tended to be couched in general terms (e.g. "signals should be positioned as near as possible to the driver's eye level"). More recent industry standards have become more detailed or absolute (e.g. the red aspect of an overhead signal should "normally be at 5.03 metres above rail level"), but generally do not require retrospective action to meet any new, more strict, requirements.

8.9 The height of signals is an important signal sighting factor. Positioning them as close as possible to driver's eye level maximises the effectiveness of the signal's beam, and signals positioned at excessive height are more likely to be obscured by overhead line equipment. The height of the signals on gantry 8, which carries signal SN 109, is broadly (within 55mm) in accordance with current requirements regarding the maximum height of signals. However, many of the other signals in the Paddington area on the approach to signal SN 109 are at a height which is in excess of that permitted by current Railway Group Standards - although when the signals were designed and installed no maximum height was specified.

8.10 The signals on gantry 8, with the red aspect offset to the bottom left in a reverse "L" formation, are an unusual design,. At the time this "L" formation was installed on the gantry (1994) the appropriate standard (British Railways Board Standard Signalling Principle No 4) showed permissible arrangements of aspects in cases where the preferred vertical arrangement could not be accommodated. These permissible arrangements did not include the "L" shape or the reverse "L". Furthermore the permissible horizontal arrangements indicated that the red aspect should be closest to the axis of the driver's eye. This is not the case with any of the signals on gantry 8. At the time of installation, procedures existed whereby non-standard arrangements could be authorised. No evidence was found that this process had been followed.

8.11 The offset from the left-hand rail of those signals leading up to, and including, signal SN109 showed wide variance from the current standard, which replicates the earlier requirements for the offset to "normally be.....0.914 metres to the left of the running edge of the near side rail...". The offsets varied from 0.590 metres to 1.505 metres (in the case of signal SN109).

8.12 Signals need to be aligned correctly to maximise their readability. This has particular importance where the signal is located on a line where the direction of travel is East-West (as at Ladbroke Grove) where low-angle sunlight can reduce readability. Beam alignment of signal SN109, the 3 signals leading up to it, and SN120 was not in accordance the current Railway Group Standard GK/RT0037 nor with British Rail Signal Maintenance Specification SG21, which was current at the time of their installation. Although of lesser significance to the circumstances of the collision, it was found that orientation of the close-range viewing sectors of 4 out of the 6 signals examined in detail were not in accordance with the current GK/RT0037, nor with SG21 which was current at the time of the installation

8.13 The overall conclusion from the W S Atkins signal sighting experts is that the complexity of the layout and the signal gantries, the range of approaches, and the obscuration of the signal aspects by overhead line equipment present an exceptionally difficult signal reading task.

9. PREVENTION OF SPADS

9.1 The phenomenon of drivers passing through red signals apparently unaware of their error is known, but comparatively rare. In the absence of an effective automated system to prevent this type of error, such as Automatic Train Protection (ATP), reliance upon drivers correctly interpreting and responding to signals alone results in potential for a residual level of risk.

SPAD history of signal SN109 and the Paddington area

9.2 Signal SN109 was one of the top 22 most SPADed signals on the Railtrack network, and its history of recent SPADs is given in the table below.

DATE	APPROACH ROUTE	LENGTH OF OVERRUN [8]	TRAIN CLASS	WEATHER	ERROR DESCRIPTION (as indicated by industry and/or HSE investigation)	DRIVER EXPERIENCE	DRIVER AGE
13 Feb 1995	Line 1	105 yds	166	Fine	Viewed wrong signal (SN111)	5 yrs	40 yrs
15 Mar 1996	Line 3	146 yds	165	Fine	Failed to check aspect at SN85	6 yrs	37 yrs
23 June 1996	Line 1	11 yds	165	Bright Sun	Failed to react to Single Yellow at SN81	4 yrs	38 yrs
3 April 1997	Line 4	72 yds	165	Bright Sun	Assumed SN109 would clear	1.5 yrs	30 yrs
4 Feb 1998	Line 4	500+ yds	143 (HST)	Fine	Failed to react to SN87. Failed to locate SN109. Misled by Flashing Yellows	34 yrs	62 yrs
6 Aug 1998	Line 4 (raw data unclear)	14 yds	166	Bright Sun	Failed to react to Single Yellow. Distracted by need to use PA	39 yrs	62 yrs
22 Aug 1998	Line 4	3 yds	165	Fine	Failed to react to Single Yellow at SN 87	37 yrs	59 yrs

[8] In contrast to the SPAD on 5 October 1999, in all the cases described in this table drivers realised their errors, albeit late, and stopped before reaching any conflict point.

9.3 Railway Group Standard GO/RT3252 requires that signal sighting committees be convened when a signal has been SPADed more than once in a period of 12 months, or 3 times in any 3 year period. Railway Group Standard GK/RT 0078 "Overrun Protection and Mitigation" also requires that a risk assessment should be carried out where a signal has a history of SPADs. The issue of previous SPAD management was the subject of detailed examination at the Ladbroke Grove Rail Inquiry, and it is not explored further in this report.

Human factors issues.

9.4 Human factor experts from HSL investigated the potential for driver human error, and their investigations included small group discussions with 29 train drivers familiar with the route taken by the 165 on 5th October. In addition, an analysis of driver tasks was performed by analysing video recordings of a driver travelling over routes of close approximation to that taken by the 165 - this involved three video cameras, one providing a forward view from the driver's cab, a second giving an in-cab view of the driver's actions, and a third giving a view from a head mounted camera worn by the driver to give an indication of where driver's attention was focused. The investigations addressed the following issues:

- influences relating to human perception and attention, particularly the amount of time available to attend to signal SN109, processing of this information, and the scope for divided attention or driver distraction;
- influences relating to how drivers assimilate and interpret displays and controls and make decisions;
- the potential for driver fatigue having played a role in the collision; and
- the extent to which features of signal SN109 could have contributed to the collision in terms of design, location, orientation and conspicuity.

9.5 The chance of human error can be considered to be enhanced where drivers have a high level of expectation regarding the likely signal aspects which will be displayed, and where the physical location of signals fails to take sufficient account of the characteristics and limitations of human sensory and cognitive processes. The human factors investigations concluded that there were a number of interrelated factors relevant to the potential for driver error on the part of Mr. Hodder:

- There does not appear to be any evidence indicating the presence of significant distractions present in Mr. Hodder's field of view on the approach to signal SN109 on the day of the collision, neither is there any record of a distraction emanating from the passenger compartment of the train.

- Within the "window of opportunity" for viewing signals, drivers may have to attend to other track and in-cab displays/controls (such potential tasks include looking at the speedometer, attending to AWS warning, looking at the trackside maximum speed boards etc.). If these actions are undertaken they would reduce from the time available to view signals. However, on the basis of an indicative task analysis, if Mr. Hodder attended to all plausible tasks (i.e. worse case) during the signal SN109 sighting window it would appear that he still had a minimum of approximately 3.5 - 6 seconds available for unobstructed viewing and undivided attention for viewing signal SN109. None of the tasks for which allowances have been made could be considered unique requirements of Mr. Hodder.

- The obstruction of the signals on gantry 8 by the transverse girders below the preceding Portobello Bridge, has the effect of presenting the lower signal aspects first to a driver. Furthermore, the red aspect of signal SN109 remains obscured for longer than the other signals on the gantry, only becoming visible some 3 seconds later than the red aspect of the other signals (when approached at the speed of the day of the collision). This apparent absence of a red aspect at signal SN109, when red aspects were visible at all the adjacent signals, led the human factor experts from HSL to identify its possible potential for misleading Mr. Hodder into making an early decision about the status of signal SN109 and hence him concluding that it was displaying a proceed aspect as its red aspect is not initially apparent. This view derived from small group discussions undertaken by HSL with drivers.

- The AWS audible and visual warnings do not differentiate between cautionary and stop aspects (contrary to established human factors advice, such as BSEN 981:1997, for effective alarm systems in general).

SPAD at signal SN109 on 5 October 1999

9.6 The investigation sought to identify why Mr. Hodder drove past signal SN109 at red despite the following:

- The red aspect of signal SN109 and all of the previous signals he passed on his journey from Paddington had sighting times in accordance with current standards, and there was no real evidence that long distance signal sighting on the day of the collision had been compromised by sun "swamping".

- No evidence was found of other distractions, either trackside or from within the train. Even if attending to driving controls or lineside signs caused him to look away, Mr. Hodder would still have had a minimum of 3.5 - 6 seconds of unobstructed viewing time of signal SN109.

- The AWS was working correctly.

- Medical and behavioural investigation did not identify any points of concern. Mr. Hodder appeared mentally well balanced, no drugs or alcohol were found in his body, and an analysis of his roster pattern indicated that he was highly unlikely to have been abnormally fatigued or suffering from a decline of alertness due to monotony.

9.7 The investigation did not identify any reasons why Mr. Hodder would have knowingly set out to pass signal SN109 at red, and there were pointers as to how the SPAD could have come about:

- Mr. Hodder was not alone in experiencing problems whilst driving in the Paddington area. Signal SN109 was one of the most SPADed signals on the Railtrack network.

- The signal sighting investigation by W S Atkins clearly identified concerns about the very challenging nature of signal sighting in the Paddington area. A number of significant factors were identified whereby the signalling in the Paddington area did not comply with relevant industry standards, and W S Atkins' overall conclusion was that the signal viewing conditions presented an exceptionally difficult signal reading task

- Although Mr. Hodder had completed the Thames Train training programme and had qualified as a driver 13 days before the collision, he was still inexperienced as a driver in charge.

- Mr. Hodder's actions immediately before signal SN109 are of crucial significance. His driving pattern whilst traveling through SN43 (at green), SN63 (at double yellow) and SN87 (at single yellow) had been highly appropriate given their status, and on the approach to signal SN109 he was coasting. However, at the point where all aspects of signals on gantry 8 were visible <u>except</u> signal SN109 he chose to accelerate from coast to Notch 5. The possibility that Mr. Hodder may have, at that time, assumed that signal SN109 was displaying a proceed aspect is discussed in paragraph 9.5.

- Very soon after Mr. Hodder accelerated to Notch 5 on the approach to signal SN109, the AWS horn operated. He then cancelled the AWS horn and immediately accelerated to Notch 7 some 107 metres before Gantry 8. There is a possibility that this cancellation could have been an automatic response, because the AWS horn does not distinguish between single/double yellow proceed aspects and the red stop aspect he may have simply mistakenly considered the AWS horn to have been a further confirmatory sign that he could proceed through signal SN109[9].

- His driving pattern indicates that Mr. Hodder did not become aware of his error of passing signal SN109 at red until just before the collision. Greater experience of driving in the Paddington area might have increased the likelihood of him becoming aware earlier that the route he was taking after passing through signal SN109 was not, as scheduled, to the Down Main but rather was taking him directly onto the Up Main, and therefore required immediate avoiding action.

9.8 This varied picture of reasons why the SPAD at signal SN109 could have occurred has led HSE to conclude that any acts or omissions of Mr. Hodder were just one group of contributory factors to consider. These issues were discussed at length during LGRI, and any further conclusions are therefore left to the Inquiry report.

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[9] During the hearings at the Ladbroke Grove Rail Inquiry, additional evidence concerning the use by Mr. Hodder of the Driver Reminder Appliance (DRA) came to light, and this could have an additional bearing on his actions. Conclusions on this issue are left for the report of the Inquiry.

10. SIGNALLER ISSUES.

10.1 The investigation looked at the emergency actions taken in the Slough Control Centre following the SPAD of signal SN109. At that time, the signalling was being controlled by Automatic Route Setting (ARS), and Mr. David Allen had overall responsibility for the workstation which controlled the signalling in the Ladbroke Grove area. He had been a signalman/signaller for approximately 16 years, of which the last 5 years had been in Slough Control Centre. He was a Grade 10 Signaller, the highest grade, with a Certificate of Competency in Rules & Regulations and subject to a competency and fitness assessment regime.

10.2 At the time of the collision, Mr. Allen had just started his seventh consecutive 12 hour turn of duty. During week commencing 26/9/99, he had worked 72 hours, the maximum permitted under the Railway Group Standard for safety critical work (GH/RT4004). After the collision he was screened for the presence of drugs and alcohol. The tests were negative.

10.3 Statements obtained by BTP and passed to HSE indicate the following. When the 165 went past signal SN109 at danger, an alarm sounded at the signaller's workstation (all alarms in the Control centre have the same sound - a short "tweet"). A monitor screen at the workstation displayed the reason for the alarm, which was the out of sequence occupation of PGE track circuit (see diagram at Appendix 1). Mr. Allen stated that after appraising the situation, and deducing that a SPAD had occurred, Mr. Allen took action to stop the HST by changing SN 120 to danger (using the workstation trackerball and operating button). This action was taken 18-20 seconds after the SPAD. At around that time, witness statements indicate that a colleague signaller on the other workstation, Mr. James Hillman, sent an automatic emergency STOP message to the driver of the 165 by means of the cab secure radio[10]. Mr. Allen stated that, having replaced SN120 to danger, he then changed the track display screen to an enlarged view of the Ladbroke Grove track layout and tried to divert the 165 from Line 3 towards the Down Relief line via 8059 points, but was prevented from doing so, possibly because by this time the 165 had also occupied PGG track circuit which correctly locked the points in the normal (i.e. straight ahead) position. The collision happened very soon after.

10.4 The time between the SPAD of signal SN109 and the collision was about 30 seconds. Calculations have shown that any emergency stop message would have had to have been sent within approx. 14 -15 seconds of the SPAD to have given Mr. Hodder time sufficient time to react and use the braking system to bring the 165 to a halt before it came into the path of the HST. Also, for Mr. Allen to divert the 165 via 8059 points to the Down Relief, he would have had to initiate this within around 12 seconds of the SPAD, but before doing so he would have needed to have assessed whether such an action would lead to a collision elsewhere. Neither the sending of

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[10]Although subsequent investigation of the telecommunications systems showed no significant problems which could have affected emergency calls being made or received, the disc from the Cab Secure Radio data logger was, unfortunately, not recovered from the Slough IECC immediately following the collision. Confirmation of the time when an emergency call was made therefore cannot be obtained.

the "stop" message nor the changing of the points were taken within the necessary time frame to prevent the collision. Even the change of SN120 to danger, which took place 18-20 seconds after the SPAD, was ineffective because by this time the HST was between 179 - 278 metres from the signal and travelling at 81-83 mph, so any resultant braking by the HST at this late stage would not have made any significant difference to the speed of impact. The investigation therefore looked at the variety of factors which affected the speed and appropriateness of response of signallers in the Slough Control Centre to a SPAD.

10.5 On the morning of the collision, train movements in the Ladbroke Grove area were being automatically signalled by the ARS, so the role of the signallers was to monitor the ARS and intervene only when unplanned/irregular train movements or events occurred, including an emergency such as a SPAD. The signallers used an array of VDU monitors and a tracker ball or keyboard to control train movements. This system means that the signaller may need to switch between a number of available displays when it is necessary to obtain detailed views.

10.6 When a SPAD occurs, the computer system warns of this by producing a single brief, and not particularly arresting, warning "tweet" from the VDU. This alarm is common to a number of occurrences requiring signaller attention (ranging from the relatively minor to the potentially serious) so does not provide a unique identification that a SPAD has happened. Nor does it discriminate between the different levels of urgency for the signallers' action required. Train movements on the VDU display are denoted by the illumination of the relevant segments of the track circuit diagram, with authorised as well as unauthorised (such as a SPAD) track occupations in the same colour (red). The speed and exact position of the train within a track circuit block cannot be deduced from this display. When a SPAD has occurred, though, the head code of the train will remain displayed adjacent to the signal on the VDU's track circuit diagram.

10.7 Railtrack's instructions to signallers in the event of a SPAD are contained in Instruction 47 Signalling General Instructions (Railway Group Standard GO/RT 3062); Regulations 4.3 & 6 Track Circuit Block Regulations (Railway Group Standard GO/RT 3062/1); and the local procedures specific to the Slough Control Centre "Instructions to Signallers at Slough New". The scope of these three sets of instructions overlap. There does not appear to have been opportunities for signalling staff to practise their responses to SPADs, for example by simulator training, other than when they happened to be on shift when an actual SPAD occurred.

10.8 The signallers from the Slough Control Centre gave oral evidence, which was tested in cross-examination, to the Ladbroke Grove Rail Inquiry. Further comment and conclusions on these issues are therefore left to the Inquiry.

11. FIRE ISSUES

11.1 Immediately after the collision there were fears that a considerable number of fatalities might have been caused by the fires on the rolling stock, particularly because of the extremely severe fire damage to the HST's Coach H. However, it was subsequently ascertained that three people had died as a direct result of fire. Nonfatal burns were mainly restricted to those passengers in Coach H and the 165's Coach B3. Apart from in Coach H and at the end of Coach B2, the only other fire internal to the coaches was that involving one seat in Coach B2.

Fire damage assessment

11.2 The work on the fire issues arising from the collision was carried out principally by HSL. A substantial record of the on-site fire damage was produced, based upon on-site observation and photographic/video records as well as subsequent examination of the damaged vehicles at Crewe. This work was of prime importance during the subsequent phases of the fire investigation.

11.3 An outline description of the damage to the vehicles is given elsewhere in this report (Chapter 3). Photographic and video records taken immediately after the crash by local residents and the press showed numerous fires, the principal one being within and around Coach H, which appears to have started soon after the initial impact occurred. There was also clear evidence of fires to the south of the middle section of the HST. These had involved both vegetation and items of debris. For many of these fires there were no obvious sources of ignition and it is therefore presumed that in such cases debris was burning before coming to rest, or was ignited either by burning fuel raining down or by other items of burning debris landing upon it.

11.4 Debris from Coach B3 of the 165 was found scattered throughout the debris field. The fragments were examined for fire damage following the two dimensional reconstruction of Coach B3 at Crewe. Although the fragments showed fire damage and soot deposition, in some cases extensive, there was no consistent pattern suggesting that the fire damage to the remnants of Coach B3 occurred after the initial breakup of the coach. The on-site fire damage assessment showed evidence of fires at the front of Coach B2 amongst the remnants of Coach B3, and to the north of Coach B2 near its western end where it came to rest against a gantry post. There was a localised internal seat fire within Coach B2, immediately adjacent to an impact puncture in the side of the vehicle - penetration was probably due to an item sufficiently hot to have caused this localised seat fire. The trailing vehicle, Coach B1, exhibited very little fire damage.

11.5 The rear power car of the HST and Coaches A-E showed little or no fire damage. Coach E, though, showed evidence of smoke ingress. There was no evidence of any internal fires or ingress of smoke into Coach F, although there was external sooting on the leading half of the Coach and some fire damage to the outside of the leading end. Coach G was heavily sooted over its entire length although only exhibiting minor fire/heat damage. There had been significant ingress of external smoke into the leading end of Coach G, and this was probably at a very early stage of the collision before the vehicle overturned.

11.6 Coach H was the most severely fire damaged vehicle on the site. A very high proportion of its combustible content had been consumed in the fire. This included GRP paneling and seat components, plywood used as carriage floors, walls, partitions and luggage racks, carpeting, plastic coverings on metal components and plastic electrical insulating materials. Large sections of the plywood decking on the floor of the carriage, though, were incompletely burned during the fire, and in a number of places the floor carpet was protected by overlying objects which provided sufficient insulation during the course of the fire to prevent them being fully consumed. There was evidence of high temperature distortion of minor structural elements in several places, and the majority of aluminium alloy fittings in the exposed upper part of the carriage had also been melted or oxidised. The exterior surface finish on the south side of the coach had been burned away to a level corresponding to the carriage floor level. A significant amount of the material of the aluminium window frames had also been completely burnt away. The north side exterior fire damage was somewhat less - most of the paint on this side of the carriage was still recognisable, although the majority of the exterior surface coatings on the roof had been burned away.

11.7 In the leading HST power car, the remains of neither the driver's cab nor the guard's compartment showed signs of any internal fire, nor any indications of smoke ingress, although the power car itself had suffered severe mechanical damage during the incident. There was no evidence of any internal fires inside the engine bay. There was, though, extensive fire damage to the exterior paint work of the power car, due to the influence of external fires.

11.8 During the collision the two aluminium fuel tanks from the leading HST power car became separated from the vehicle. These tanks have capacities of 2710 and 1966 litres respectively and were connected by a flexible hose. The larger tank suffered severe impact damage and crushing (its volume was reduced by about a half) and was found at the eastern end of Coach H. The smaller tank had been penetrated by a section of the 165 aluminium flooring from Coach B3, and had broken up into several fragments.

11.9 The fuel tank from the leading 165 Coach B3 (1464 litres capacity) was located originally under the front door set, some 6.5 metres from the front of the coach. In the crash it suffered a rapid catastrophic failure, and the impact shattered it into about 20 fragments. The other two coaches of the 165 had similar fuel tanks, and although neither suffered a catastrophic failure similar to that of Coach B3, both failed sufficiently for their contents to drain out at the crash scene, thus allowing a liquid pool to form within the porous trackside ballast. Overall, the failure of five tanks led to just over 6000 litres (almost six tonnes) of fuel being released, principally to the south of the HST Coaches B-F.

Examination of the fuels

11.10 Samples of fuel from both trains, and from the fuel storage facilities at their respect refueling depots, were obtained. Detailed analysis has shown that the composition of these fuel samples was consistent with gas oils (diesel) meeting the specification for a middle distillate fuel of Class A2 of BS2869:1988. There was no added petrol fraction in either fuel.

11.11 The HST fuel was a summer grade gas oil, whereas that for the 165 was a winter grade gas oil. The difference in the flash points (80-82°C for the HST and 65°C for the 165) is consistent with this, and the flash points for both fuels are well within the minimum flash points requirement of 56°C for a middle distillate fuel conforming to Class A2 of BS 2869: 1998.

11.12 The auto-ignition temperature of the HST fuel was in the range 235-240°C, and the corresponding range for the fuel from the 165 was 240-245°C.

Investigation into the overall fire dynamics

11.13 The investigation aimed to ascertain how the diesel fuel from both trains behaved during the collision, and how it subsequently contributed to the development and spread of the fire. This work built on the fire damage assessment and identification of ignition sources, and involved considerable analysis of written statements from passengers and other witnesses. To help establish the fire dynamics following the initial collision fuel release from the fuel tanks was modelled on a theoretical basis, which was followed up by small scale and then full scale testing.

11.14 The damage to the various fuel tanks, causing the release of up to six tonnes of diesel, is described in paragraphs 11.8 & 11.9 above. The investigation concluded that the fuel release during the early stages of the incident was predominately from the 165, due to the catastrophic failure of the coach B3 fuel tank soon after impact. This had created sufficient compression and overpressure inside the tank to cause atomisation of released fuel, and hence the formation of a cloud of dispersed, easily ignitable, diesel fuel. At around the same time as the tank under B3 disintegrated, the smaller of the leading HST power car tanks also failed violently and released its fuel, possibly also under pressure. It is believed that the rate of fuel release from others tanks damaged in the collision was somewhat slower. The larger of the two HST power car tanks became detached at an early stage retaining a high proportion of its fuel, and either rolled or was pushed, leaking fuel along its path, to its final resting position just to the east of Coach H. The fuel tanks of Coaches B2 and B1 ended up still attached to their respective vehicles, albeit significantly damaged. It is likely that in the first minutes after the collision fuel leaked from them under gravity onto the surrounding ground, and then soaked into the track ballast.

11.15 As a result, fuel appeared widely distributed over the site, largely on the South side of the HST between the point of impact and the final resting position of

Coach H. There was evidence of ingress of diesel fuel into Coach H and diesel fuel deposition onto the sides of Coaches H, B1, B2 and the leading HST power car.

11.16 Soon after impact there was an event widely described by witnesses as a "fireball", with flames passing down the outsides of both trains accompanied by a large amount of smoke and high radiant intensity. Photographic evidence obtained from the security camera at the Sainsbury's supermarket to the north of the site confirms this, and shows the vertical extent of the fireball to be in excess of 22m and the region of turbulent burning extending a significant distance along the track in the direction of Paddington. HSL fire experts considered the mechanism for this fireball to be the ignition and rapid combustion of a highly turbulent fuel rich cloud of dispersed diesel fuel arising from the release of fuel under pressure from the tank underneath Coach B3. The best estimate of the quantity of fuel in the fireball is about 500 kg, which amounts to almost all the fuel available from that tank. Ignition of this cloud could have been from a variety of sources, including the overhead power lines. Further details of likely ignition sources, and of the experimental work subsequently carried out to replicate this fireball mechanism, are detailed in paragraphs 11.22 & 13.16 - 13.20.

11.17 Some items of debris from the breakup of Coach B3 were set alight by the fireball, either as a result of their combustibility or being soaked by diesel from the initial impact. There was also fallout of significant quantities of burning fuel which contributed to a large number of trackside fires around the site, igniting vegetation at the trackside and items of debris from the collision. These fires produced significant amounts of smoke.

11.18 Other trackside fires occurred as a result of direct spillage from the fuel tanks. These linear fires were observed on the ballast alongside the south sides of Coaches D and E, and between the 165 and the HST. They produced flames of significant extent reaching up to the height of the windows, and smoke from these fires entered adjacent carriages. However, due to their location on the ballast these fires were generally of short duration as the fuel drained through the permeable surface.

11.19 Apart from the fire in coach H and evidence of fire at the western extremity of B2 where the rear of B3 had been pushed back during the collision, there was only one other fire inside the coaches. This involved a seat and insulation in the centre of B2 which appeared to have been caused by the penetration of the body shell by a burning object.

The fire in Coach H

11.20 The fire in Coach H was more severe and of longer duration than those fires which occurred elsewhere. It grew quickly over a period of minutes to involve a very high proportion of combustible materials on the vehicle. Over a period of 30 minutes most of the vehicle was consumed down to its steel frame. The fire produced large amounts of dense black smoke, flames 2-4 metres high, and internal temperatures of up to 900°C. Considerable investigative work was undertaken to establish why Coach H was so severely burnt in comparison with the other coaches.

11.21 The progress of the fire in coach H can be divided into three distinct phases:

(i) Crash phase. This lasted for less than 18 seconds whilst Coach H collided with the rear of the leading HST power car, rotated through virtually 180°, and finally came to rest inclined at an angle of 25-30° to the horizontal. As well as witnessing the external fireball, those in the rear of Coach H (which because of the rotation became the front) were engulfed in an internal fireball which progressed down part of the carriage (one witness said that this fireball lasted "about 10 to 15 seconds"). This fireball was mainly responsible for the burn injuries suffered by those inside the coach. The descriptions by witnesses of the fireball are consistent with an ignited spray of relatively large droplets of dispersed diesel fuel entering the carriage, and the most likely route for this contamination by diesel spray is considered to be via the rearmost window on the north side of the coach. This window was damaged early in the crash phase, and as the carriage swung round the open window would have been facing the direction of travel and thus any diesel droplets in its path would have been forced into the interior. Subsequent test of ash samples from the debris in Coach H demonstrated the presence of diesel fuel inside the coach.

(ii) Pre-flashover/evacuation phase. This phase lasted for 2-3 minutes whilst the fires in the coach were confined to isolated ignited objects. The overall impression of witnesses is of a series of small fires with flames around 0.3 metres high, with a larger fire at the previously damaged rearmost window. At this stage the burning must have largely involved the diesel that had entered the coach, together with relatively easily ignited items such as paper. Smoke logging of the coach was severe but escape was possible.

(iii) Flashover phase. Eventual levels of downward radiation from flames at ceiling level can be expected to lead to a very rapid extension of flame to involve all flammable surfaces in the coach. This flashover phase was witnessed by many survivors and was also recorded in a sequence of photographs taken by a member of the public. An accurate determination of the time intervals between these photos, and hence the speed of fire spread, was possible using detailed measurements of the progress of various shadows visible in the photos themselves. It was clear that the fire spread over three double bays of seats in just over a minute, and had progressed down the entire coach within 7 minutes of the collision.

11.22 Part of the subsequent fire investigation sought to examine the degree of fire resistance exhibited by the HST internal coach fittings. A series of experimental tests showed that it was extremely difficult to obtain sustained burning of HST First Class coach interior materials and components. However, where significant quantities of diesel were used, fire was sustained. The tests culminated in a mock up of two complete bays of single and double seats, corresponding to one quarter of the interior of a full carriage, using seats, tables, lining panels and other fitments taken from Coaches F and G. The mock up was constructed in a freight container set at an angle to reproduce the orientation of Coach H after the collision, and with a number of vents corresponding to the broken windows etc. 2kg of diesel fuel was applied locally to the seats at one end and ignited. The test showed that once the fire became established across a row of seats the process of flashover occurred very rapidly, around four minutes after ignition The observed rate of fire spread was consistent with that seen at Ladbroke Grove.

Assessment of ignition sources

11.23 The most likely sources of ignition for the fuel from the initial failure of Coach B3's fuel tank was contact with the 25 kV overhead power lines, heat and sparks produced by impact between aluminium and rusted steel (a vigorous chemical reaction, known as the thermite reaction, can occur between aluminium and iron oxide, and this produces heat and showers of sparks), and powerful electrical discharges produced from the batteries or their associated wiring on both the HST and 165 trains. Forensic evidence was found that each of these mechanisms occurred during the crash, and any one of them could have ignited the fuel. For the case of the overhead power lines there is also documented evidence recorded by the protection relay systems. Although there were other potential sources of ignition it is less likely that these caused the ignition, because of either their lower incendivity or the specific circumstances relating to the crash.

11.24 Experimental work demonstrated that energy levels equivalent to about 1% of that available in the overhead power supply can ignite a pool of diesel and that short-circuiting a single two volt battery cell of the type used on the 165 will ignite a diesel spray or that three such cells will ignite a flowing film of diesel. A thermite reaction has also been shown to ignite diesel sprays.

12. SPEED AND EASE OF MEANS OF ESCAPE

12.1 The speed and ease of egress from rolling stock following an impact is a vital consideration in the presence of fire. The escape of passengers from the two trains at Ladbroke Grove progressed, for the most part, in an atmosphere of calmness and consideration for fellow passengers. However, investigation work was subsequently conducted to identify influences on passenger behaviour in relation to the escape strategies they adopted, any ergonomics issues relating to the design of rolling stock and ease of emergency egress, and in particular to:

- ascertain whether the means of escape from the coach doors functioned adequately; and
- assess the performance of the emergency glass window hammers.

HST Doors

12.2 The HST (in common with all other HSTs) was fitted with a central door locking system. This allows all the doors along either side of the train to be locked or released by the guard. In cases of emergency, each door can be unlocked from the inside by operating an egress valve situated above the door - the plastic covering sheet must first be broken and the emergency egress lever pulled to withdraw the door locking bolt.

12.3 A full set of test procedures for the central door locking for the undamaged Coaches A-D was carried out shortly after the collision. The test revealed no evidence to suggest that the central door locking system would have impeded egress from any of these coaches, and it is concluded that the central door locking system was operating correctly.

12.4 However, the evidence of a number of witnesses suggests that the failure to open some of the external doors of the HST was the result of the first passengers to reach them not being aware that the emergency egress levers needed to be pulled to release the central door locking mechanism and/or that the conventional door handle had to be used once the lever had been pulled. Although information about the use of emergency door release levers is provided adjacent to the devices themselves, signs relating to the additional need to operate the external door handle are only revealed once the emergency lever has been operated. No information relating to the operation of emergency egress levers is displayed in the seating compartment. In emergency situation the likelihood of individuals paying attention to written instruction is reduced and cannot be relied upon.

12.5 Each coach of the HST had single-leaf automatic sliding vestibule doors located between the end of the seating area of each coach and the vestibule. These doors are normally closed, in order to prevent draughts and noise from the vestibules reaching the passenger compartment. They automatically open when passengers stand on pressure mats located under the carpets on either side of each door. Egress via an adjacent coach or the external doors would be impeded if an automatic vestibule door could not be opened in an emergency. Therefore, the investigation included an examination of these doors.

12.6 All of the automatic vestibule doors in Coaches A to D bar one (at the front of Coach C) were found to have been damaged, possibly as a direct result of the deceleration resulting from the impact or passengers pressing against the doors during the deceleration. This damage affected only the automatic operation, and tests indicated that these doors could have been opened manually with little difficulty. When Coach E was examined at Crewe it was found that both of the automatic vestibule doors were binding over part of their travel and much greater forces than normal were required to open these doors.

12.7 Both automatic vestibule doors in any one coach open towards the same side of the coach. If a coach ends up on its side following a collision, these doors will therefore either open with, or against, gravity, depending on which side of the coach is uppermost. The orientation of the coaches that ended up tilted (F) or on its side (G) was such that their automatic vestibule doors had to be opened against gravity. One of these (at the front of Coach F) was opened with no mention of difficulty by a passenger following the incident but other passengers found it necessary to smash open another automatic vestibule door (that at the front of Coach G). Subsequently, tests were carried out on the HST rolling stock at Crewe to establish the forces required to open vestibule doors. This work identified that the forces required to open an unpowered vestibule door in its normal orientation was within the capability of nearly all able bodied adults. However, when a carriage is overturned, and the vestibule doors are closed in a horizontal orientation (as happened in some of the HST coaches at Ladbroke Grove), the force required to open them is likely to lie beyond the capability of most females and more than 10% of adult males.

165 Doors

12.8 For the 165, each coach has 4 pairs of pneumatically operated sliding plug doors (two per side at 1/3 and 2/3 along the bodywork). Passenger egress devices (door release handles behind breakable covers) are situated in the door header panels. Pulling the release handle will either (if air is still in the system) move both door leaves out, enabling them to be pushed open or (if there is no air in the system) open one door leaf out, enabling it to be pushed open whilst the second leaf remains locked in position. The sliding doors can also be operated via door access handles outside the coaches, one on each side. There are also gangway doors between coaches.

12.9 The investigation found no evidence to suggest that egress facilities were not functioning correctly prior to the collision. However, the condition of the 165 doors was also examined to establish their functionality with regard to means of escape following the collision.

12.10 Coach B1 ended up on its side, so two sliding doors were against the ground, effectively preventing egress. The other two sliding doors were, effectively, in the roof position, and although tests showed that they were capable of operating correctly, egress through them would have been very difficult because of their inaccessibility. A primary escape route in Coach B1 was via the rear driving cab door window, this being facilitated by the fortuitous presence of Thames Trains staff travelling in the rear cab. The gangway doors direct into the open air (Coach B1 had separated from Coach B2) could not be fully opened to their full extent due to substantial damage in the adjacent floor area.

12.11 Coach B2 was upright, but with severe damage at the front end, nearest to Coach B3. On one side egress was impossible, as one pair of doors was jammed against a trackside electrification mast, and the other pair could not be opened due to the external footstep being bent upwards in the collision, preventing the doors from being able to move outwards. Similar footstep damage prevented the operation of one pair of doors on the opposite side, but the fourth pair was able to be opened satisfactorily. The rear gangway door was jammed in the closed position due to collision damage to the bottom door runner.

Window glass hammers

12.12 Communication issues were apparent in relation to the use of window glass hammers in the HST[11]. Each coach had four hammers, each stored in a container with a plastic cover. A notice on and within each container states that the hammer should be applied to the corner of windows, but it is in fairly small text. The associated pictograms appear to be designed to convey this same message, but their clarity could be improved. Although there was fairly widespread use of these hammers (nine hammers had been removed from their holders, and the plastic in front of the holders of a further three hammers had been broken but the hammers left in place), the success of their use varied, and it was apparent that the need to aim hammer blows at the window corner was not appreciated by some users.

12.13 At least one glass hammer failed in use. Subsequent analysis of the broken hammer handle showed that it had failed by brittle fracture, possibly as a result of the plastic handle being unable to cope with the high strain rate produced by impact[12]. This could have been as a result of using the hammer away from the window corner, where a higher impact is required to break the window as flexing of the glass reduces the effective impact force. Where hammers were used at the window corner there was evidence that they worked effectively and without damage to the hammer.

12.14 Neither the hammer containers nor the emergency door release levers had any provision to help passengers locate them in poor visibility (such as in smoke or

[11]There were no glass hammers on the 165, as they had been withdrawn from use following a significant number of thefts and their subsequent use in criminal activities both on and off the railway.

[12] This issue was more fully explored in LGRI

failed lighting). One passenger from Coach H said that he searched for a hammer but could not locate one "as it was pitch dark" because of smoke.

Other escape issues

12.15 Significant obstacles to the means of escape were created when carriages came to rest on their sides, as the doors and windows through which escape could be made were now, in effect, in the roof space. The primary exit routes became the open ends of the coaches where they had become decoupled, although there were problems to be overcome due to the orientation of the vestibule doors on the HST. At least one passenger in Coach F tried to open an external door in the roof space, but reported that the door was too heavy to open in this orientation. Some passengers were successful in gaining an exit either via windows or doors in the case of Coach B1, but a fair amount of cooperative effort or ingenuity was required (one passenger used a bicycle as a type of ladder to climb up to the roof space).

12.16 Issues of speed/ease of means of escape from railway carriages were covered in some depth by the Ladbroke Grove Rail Inquiry, and the detailed technical reports which are summarised in this Chapter formed a significant body of evidence considered by the Inquiry. Any conclusions and recommendations relating to means of escape and emergency equipment are therefore left to the Inquiry.

13. CRASHWORTHINESS ISSUES

Vehicle reconstruction and structural inspection

13.1 Following the collision, all the damaged vehicles and 18 rail wagon loads of debris from the site were taken to the ADtranz depot at Crewe.

13.2 A limited reconstruction of the leading 165 vehicle was undertaken. This required painstaking sorting through the 18 wagons of debris, and resulted in a two dimensional reconstruction, involving at least 80% of the floor, roof, sides and ends.

13.3 Following completion of this two dimensional reconstruction, a detailed survey of all the damaged coaches was completed. From this a record of damage and component failure was compiled, principally by looking at the main structural members but also considering some fractures in secondary members.

13.4 Sixty six weld and material samples were taken from the various damaged vehicles, and were subject to a programme of metallurgical studies by HSL and TWI (formerly The Welding Institute). The actual material specification and observed weld qualities were compared to the original specification, the design intent and good welding practice.

13.5 The 165 train was manufactured in 1992 by ABB, York. The body shell is a stiff monocoque structure primarily fabricated from extruded aluminium alloy (6000 series) components. The vehicles are supported on steel bogies and have aluminium fuel tanks suspended beneath them. The material properties tests confirmed that the materials used in the construction of the 165 body structures and fuel tanks generally complied with the respective specifications. Any minor discrepancies found were not significant in terms of the structural integrity of the vehicles.

13.6 The main structural members consist of a series of longitudinal aluminium alloy extrusions at floor and roof level, with vertical pillars at the ends and between the positions of doors and windows. The strength of welding filler alloys used for welding 6000 series aluminum alloy are normally inherently weaker than the parent metal itself and this, coupled with a drop in material strength caused by the heat affected zone created adjacent to the weld itself, means that it can be anticipated that structural failure will predominately be associated with the area around welds for the extreme conditions of such a high speed collision. This was the case with the 165. Overall, though, the observed quality of welding was satisfactory and appropriate for this type of fabrication and design

13.7 The damage to the HST, fabricated mainly from steel, was significantly less apart from the front of the HST power car which had been directly involved in the impact with the Coach B3. The materials of construction meant that the welds on the HST did not under-match the strength of the parent metal, and they exhibited a much better failure performance than the Class 165 aluminium vehicles.

13.8 Both trains were equipped with aluminum alloy fuel tanks, which were essentially welded thin sheet metal boxes suspended under the trains. Both tanks on the HST leading power car and all the tanks on the three 165 vehicles were damaged to some degree (in the case of the tank from B3, catastrophically) due to external impacts with other objects or the track during the collision, leading to escape of diesel fuel. There was no evidence of any significant weld or other pre-existing defects in any of the tanks. Further details on fuel tanks is given in paragraphs 13.16 - 13.20.

13.9 During the collision a total of eleven bogies became detached, nine from the front half of the HST and two from the 165, as well as three wheelsets (all from the 165). The investigation identified the various mechanisms by which bogies/wheelsets became detached. Bogie retention during rail vehicle collisions presents a safety dichotomy - on the one hand, allowing bogies to break free provides a means of dissipating energy from the vehicle during the collision but on the other hand there are potential adverse crashworthiness implications. If a bogie becomes detached it can become an obstacle to the bogies of other vehicles that are following in its path, or it can become a projectile (for instance, the front bogie from the leading 165 vehicle travelled over 100 metres after breaking free during the collision). Bogie retention also has post-collision stability implications, as none of the three HST coaches which lost both bogies remained upright when they came to rest.

Performance assessment

13.10 The Class 165 aluminium based vehicles suffered greater damage than the HST steel vehicles during the collision. A programme of work was therefore conducted by W S Atkins to compare the crash performance of aluminium and steel, particularly with respect to the vehicles of the generation involved in the Ladbroke Grove collision. This work did not attempt to replicate the Ladbroke Grove collision, but looked for gross differences in crashworthy performance, particularly to understand how such vehicles would have behaved under less onerous impact conditions than those encountered at Ladbroke Grove.

13.11 The most realistic method of comparing crash performance would have been via full scale testing, but the high costs and the long timescale limited the practicality of that option. Instead, a dynamic finite element analysis approach was adopted, a technique which is widely used in the automotive and rail industries to develop crashworthy designs. This generates a computer based model of the rail vehicle, which can then be subjected to simulated impacts covering a variety of velocities. The subsequent behaviour of the model in these simulated impacts can then be studied.

13.12 Detailed finite element models were completed for a Class 165 vehicle, a Class 43 HST Locomotive cab and a Class 321 vehicle. The latter Class was not involved in the Ladbroke Grove collision but was chosen as an equivalent steel vehicle to 165s. Whilst they are not identical to Class 165 vehicles, the Class 321

Electrical Multiple Units have a similar door location, were manufactured at a similar time, and are required to perform similar tasks.

13.13 Class 165 vehicles were manufactured in 1992, at which time there were no applicable crashworthiness standards. Current crashworthy design requirements are specified in the Railway Group Standard GM/RT2100, and new rolling stock is tested against these by conducting quasi-static crushing tests on a full scale mock-up of the section of carriage forward of the front bogie attachment point, excluding in the mock-up any couplers or bogies. To compare the Class 165 vehicle design to current standards (and the steel equivalent Class 321) a number of such quasi-static crush scenarios were therefore modelled. These tests indicated that the aluminium Class 165 was much stronger than allowed by the current standard, whereas its steel equivalent Class 321 performed more closely to that standard.

13.14 A number of dynamic impact scenarios were also modelled for both the 165 and the 321, considering impact with an HST locomotive at a number of different speeds and vehicle offsets. From this dynamic analysis, the higher stiffness of the Class 165 structure resulted in higher decelerations, but with a more robust collapse mode - as a result, the Class 165 typically absorbed more energy that the Class 321. However, the under-matching of welds in the aluminium structure (see para 13.6 above) resulted in predicted bodyshell fragmentation at impact speeds above 15 mph, which could result in opening up of passenger compartments along longitudinal weld lines and increasing the risk of sudden loss of structural resistance to collapse, occupant ejection, debris intrusion and the generation of large jagged edges and missiles. On the other hand, the higher ductility of the steel structure of the Class 321 resulted in lower decelerations and less propensity for the bodyshell to fragment, but at the expense of a higher risk of global deformation of the passenger compartment and associated increase in crushing injuries due to loss of survival space.

13.15 This work identified that quasi-static low speed crush tests, as required by the existing Railway Group Standard GM/RT2100, may not be a good indicator of the actual crashworthiness performance of rail vehicles. The modelling undertaken showed significant differences in the prediction of failure modes and locations when using the dynamic assessments compared to the quasi-static scenarios.

13.16 The dynamic modelling showed that comparison between the crashworthiness aspects of the aluminium bodied Class 165 and its steel equivalent Class 321 were not straightforward, although did indicate where design improvements could be made, such as by utilising the positive benefits of shear out couplers. The topic of crashworthiness was covered in some depth as part of the Ladbroke Grove Rail Inquiry, and the detailed technical reports which are summarised in this Chapter formed a significant body of evidence considered by the Inquiry. Any conclusions and recommendations are therefore left to the Inquiry.

Impact resistance of fuel tanks

13.16 As part of the Ladbroke Grove investigation, HSL undertook experimental work supported by theoretical studies to simulate the failure at reduced scale of type 165 fuel tanks when subjected to impacts representative of those likely to have occurred during the incident.

13.17 The theoretical studies considered the range of fluid pressures within the fuel during impact and hence the likelihood of fuel being atomised upon release. Ignition sources were examined and the three most likely ones identified. Three impact tests were then undertaken in which a scaled fuel tank, based on a class 165 design, was used. The linear dimensions of the fuel tanks were 66% of full scale, hence their internal volume was approximately 29% of an actual tank.

13.18 The test tanks were mounted on a 5 tonne sliding truck and were then impacted at a velocity of about 18 metres/s (40 mph) by a 3 tonne mass representative of a typical coach bogie. The test tanks were crushed between two platens such that their liquid contents were compressed and released under pressure. The tanks used in the first two tests contained water stained with a fluorescent dye, whilst the third test was conducted using diesel fuel. In all three tests the impact and subsequent behaviour of the tanks and their contents were videoed and filmed, both at normal and at high speed, and the tanks themselves instrumented to record internal tank pressures etc. Upon impact, the tank contents were released and observed to form an aerosol cloud which was carried away by the wind. In the case of the third test this was subsequently ignited upon contact with an ignition source consisting of a small tray of burning diesel fuel. The amount of diesel released was 320 litres, some of which upon ignition produced a fireball of some 30-40 metres diameter, with a peak temperature in excess of 1300°C and an actual surface emissive power of about 130 kW/m^2.

13.19 The final test illustrated the linkages from impact to release of fuel in an atomised state to ignition and production of a fireball. The sequence seemed to accord with the eye-witness statements and the Sainbury's security video showing the first few seconds of the incident. Both the incident and these tests illustrated the vulnerability of fuel tanks and the propensity of the diesel once released to ignite creating a fireball with its attendant fire hazards.

13.20 In examining the forensic evidence both the fire and crashworthiness experts in their joint statements to the Ladbroke Grove Rail Inquiry commented upon these points. As part of longer term industry/HSE funded research, HSL are now conducting a further set of fuel tank tests, investigating a number of possible mitigation techniques in tank design.

Performance of internal fixtures and fittings

13.21 The investigation sought, by evaluating the damage within the passenger compartments and reviewing witness statements, to establish possible links between the performance of internal fixtures and fittings and the injuries received by passengers. Considerable effort was made by BTP to recreate seating plans, and work was then undertaken to match injuries received to seating location at the time of the collision. All the vehicles suffered some degree of internal damage, and some passengers from every vehicle suffered some form of injury. In both vehicles, many passengers suffered injury from impacting the back of the seat or table directly in front of them.

13.22 An analysis of witness statements provided by BTP to HSE indicates that passengers in the HST had more opportunity to brace themselves before the collision (either by pushing against tables or by gripping armrests) than those in the 165. Consequently, HST passengers generally remained in their seats (except where the particular coach toppled over) and injuries consisted mostly of whiplash type injuries or minor injuries to faces, chests, arms and knees. All the HST vehicles suffered significant damage to tables (for instance, in Coach G all the double tables and half the single tables suffered damage) but table failure appears to have been a relatively gentle process with none of the table tops acting as projectiles. People standing appeared to fare worse than those sitting - those standing in Coach F (the buffet) fared worse than those sitting in the same coach, and of the six fatalities in Coach H, three had been standing.

13.23 Coach H received extensive collision damage, and the interior was subsequently severely damaged in the fire that followed. A detailed assessment of internal fixtures and fittings for internal crashworthiness purposes was therefore not possible.

13.24 All three coaches of the 165 suffered serious external damage. Coach B3 disintegrated on impact, and there are clearly greater crashworthiness issues than internal fixtures and fittings - these were discussed in paragraphs 10.10 - 10.15 above. In Coaches B1 and B2 a number of seats suffered severe damage from external sources, such as when the trailing end of B3 had been pushed inside the leading end of B2.

13.25 In both the HST and the 165 there was a significant volume of loose items such as luggage and loose trim (e.g. lighting grilles). Although some passengers were hit by these items, none recorded significant injuries as a result.

13.26 The topic of internal crashworthiness features was covered in the Ladbroke Grove Rail Inquiry, and the detailed technical reports which are summarised in this Chapter formed a significant body of evidence considered by the Inquiry. Any conclusions and recommendations are therefore left to the Inquiry.

14. HSE ACTIONS AFTER THE LADBROKE GROVE COLLISION

14.1 Three days after the collision at Ladbroke Grove, HSE issued three enforcement notices relating to specific hazards identified in the investigation:

i) A Notice prohibiting the use of specific routes leading up to signal SN109, until Railtrack provide effective means for preventing further SPADs at this signal.

ii) An Improvement Notice requiring Railtrack to install additional controls at the 22 signals which Railtrack's own analyses identified as leading to the greatest number of SPADs. The controls were to be in place by 6 November 1999 at the latest.

iii) An Improvement Notice requiring Railtrack to produce a timebound plan for developing a means to reduce the risk to 168 other signals where three or more SPADs had occurred in the five years up to 8 October 1999, as well as the "top 22" in the first Improvement Notice. The plan was to be produced by 6 November 1999.

Railtrack appealed against all three Notices.

14.2 Under the Health and Safety at Work etc. Act 1974 Prohibition Notices remain in force during the appeal process, and the appeal against the Prohibition Notice was heard on 30 November and 13/14 December 1999. Railtrack's appeal was dismissed by the Tribunal but Railtrack appealed against this decision to the Divisional Court. The Divisional Court hearing is due to be heard on 16 January 2001.

14.3 Paddington station was reopened on 21 October 2000 with a modified track and signalling layout determined by Railtrack and discussed with HSE. Speed, route and traffic direction restrictions were imposed, such that signal SN109 was not required to be in use. These operational restrictions will remain in place until infrastructure changes have been agreed between HSE and Railtrack and they have been implemented. This process may take two or more years. Railtrack have made a commitment to fit TPWS to the first four interlockings out of Paddington by October 2001.

14.4 An appeal against an Improvement Notice suspends its effect. Thus the date by which these Notices should have been complied with was set aside pending the outcome of the appeals. Railtrack's appeal against the first Improvement Notice relating to 22 multiple-SPAD signals (including signal SN109), was heard during March 2000. The appeal was dismissed although the Tribunal modified the Notice and extended the date for compliance to 22 May 2000. Railtrack immediately requested the Tribunal to review their decision but the Tribunal dismissed their application. Railtrack then appealed to the Divisional Court against the Tribunal's decision on this Notice, and the compliance date has therefore again been set aside pending the decision of the Divisional Court.

14.5 Railtrack's appeal against the second Improvement Notice relating to all signals which had been passed more than twice in the 5 years up to 8 October 1999, 190 signals in all, was heard during 4 April 2000. The appeal was successful, and the Notice was quashed.

14.6 Notwithstanding these appeals, HSE and specialists from W S Atkins have independently assessed the "top 22" signals and have identified additional reasonably practicable measures which could be taken. These have been discussed, and in most cases agreed with Railtrack. Further work is now concentrating on all other multiple-SPAD signals.

14.7 Immediately following the collision HSE required Railtrack to report, on a daily basis, the details of all SPAD incidents occurring on Railtrack's infrastructure. On receipt, these reports are categorised into one of three action levels, dependent on the actual and potential severity of the incident. The action taken by HSE then ranges from reviewing the adequacy of the industry's own SPAD investigation through to carrying out its own independent investigation of the most serious SPADs. Ministers are sent weekly and monthly statistical updates, the latter appearing on HSE's Internet website.

14.8 Action was also taken at an early stage to discuss particular emerging problems with the railway industry. This included:

a) A letter on 7 October 1999 to Mr. Richard George, Managing Director of First Group Train Companies, seeking confirmation of an oral commitment to do everything possible to keep ATP equipment in full functional order on Great Western HSTs. A confirmatory reply was subsequently received.

b) Letters sent on 8 October 1999 to all train operating companies (TOCs) relating to briefing of all their drivers on signals passed at danger (SPADs) and the ways of avoiding them. The letter built on and in some cases reinforced actions demanded by HSE's 1999 report on SPADs[13], which drew together the conclusions from a national HMRI inspection initiative. The letter required action by TOCs to ensure that their drivers received briefings on the most likely reasons for SPADs; the identification of any signals on their routes which are known to have been the site of SPADs, and the need to adopt defensive driving techniques. The letter also required TOCs to review their driver training, competence assessment and driver monitoring arrangements to ensure that all drivers are competent to perform their

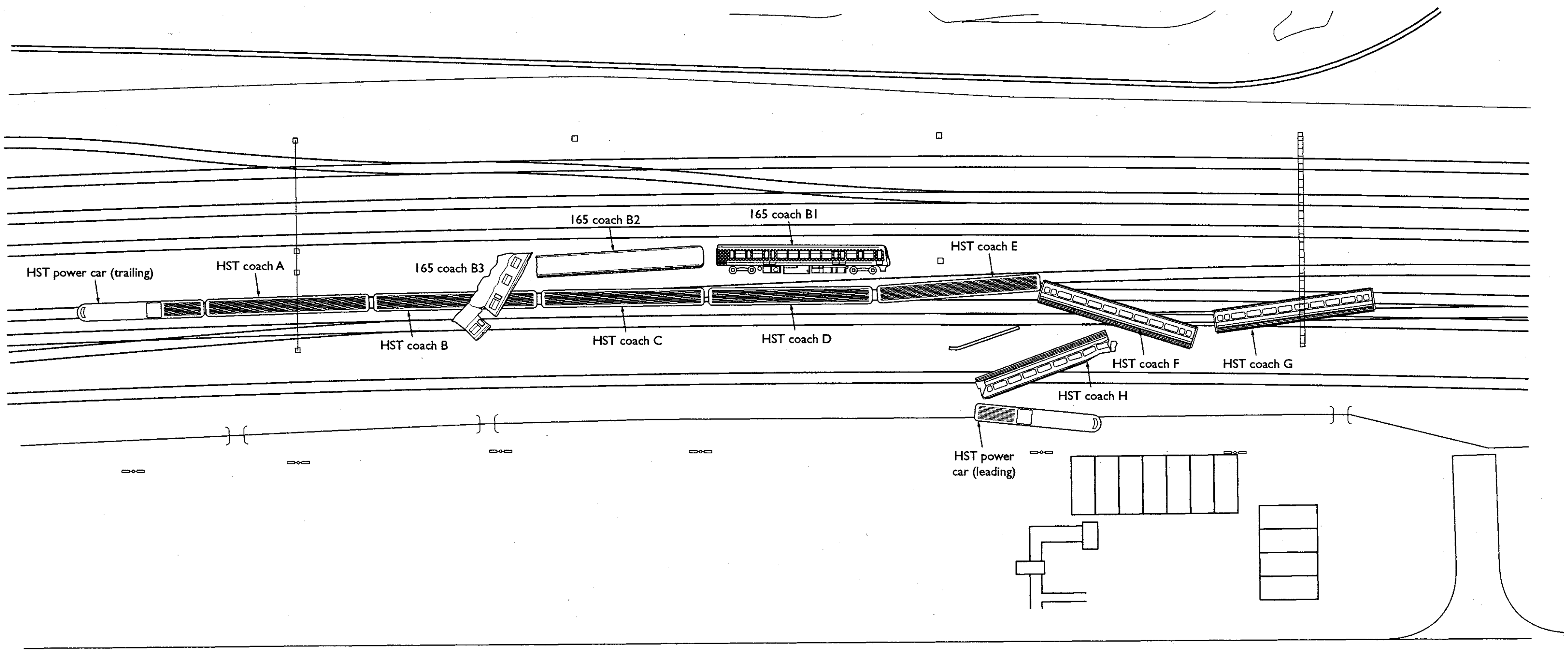
[13]Report on the inspection carried out by HM Railway Inspectorate during 1998/99 of the management systems in the railway industry covering Signals Passed at Danger - Issued 2 September 1999

duties. Following this, the Rail Industry Training Council (RITC) at the request of HSE developed a top up briefing for the rail sector on defensive driving, which was completed by the end of December 1999. It was briefed across the industry between January and March 2000. A more developed standard is also being put together by RITC to join their existing National Occupational Standards, and the Association of Train Operators (ATOC) has also subsequently developed new codes of practice covering driver training and competence issues.

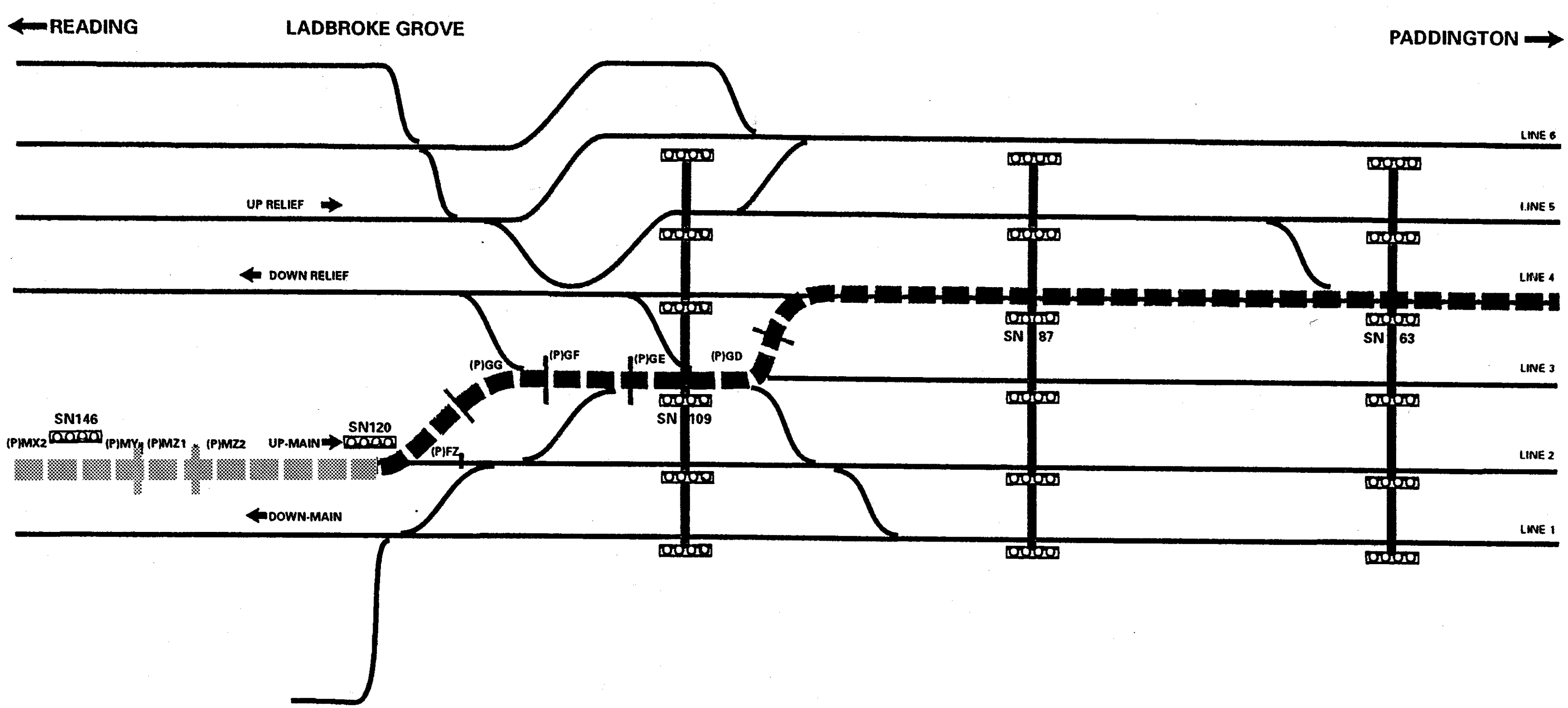
c) HSE's 1999 report on SPADs (see b above) required actions on Railtrack and TOCs to address key issues. Railtrack and all TOCs submitted their plans and HSE reviewed them for adequacy, seeking further information where necessary. HSE agreed all the 38 TOC action plans, and progress is regularly monitored. It is anticipated that all the actions will be completed by the end of March 2001.

14.9 Following the identification of the potentially confusing/conflicting instructions to signallers at the Slough IECC in the event of a SPAD (see paragraph 10.7), confirmation was obtained from Railtrack that clearer instructions had been issued.

Appendix 1: Track layout of the collision site



Appendix 2: Diagram of collision site



Appendix 3: Listing of HSL/Atkins/AEA reports

Report Number	Title
WSA 990XXA	First Prelimonary Investigation Report
WSA 99184	Assessment of A C Power Supplies
WSA 99185	Assessment of SSI Data Link Performance.
WSA 99186	Post Incident Testing of Signal Modules Controlling functions of Signals SN120, SN109, SN87 and SN63.
WSA 99187	Testing of Signal Modules Controlling Gantry 8 Signals SN105, SN107, SN111, SN113 & SN115.
WSA 99188	Post Incident Testing of Trackside AWS Equipment for Signals SN120, SN109, SN87 & SN63.
WSA 99189	Post Incident Testing of Trainborne AWS Equipment from Thames Turbo Unit 165115
WSA 99190	Post Incident Testing of Signal Head Equipment from Signals SN120, SN109, SN87 & SN63.
WSA 99191	Post Incident Testing of Trainborne AWS Equipment from Great Western HST 43011.
WSA 99192	Effect of Vibration on Automatic Warning System used on Thames Turbo Train
WSA 99805	On-Site Testing of Lineside Signalling Equipment
WSA 99806	Second Preliminary Report.
WSA 99807	Train Speed Calculations from the ARS Logging tape.
WSA 99809	Trainborne Data Recorder Analysis
WSA 99810	SSI Tape Analysis
WSA 99811	IECC Tape Analysis
WSA 99814	SSI Geographic Data Design Check
WSA 99816	Telecommunications Systems
WSA 99817	Signal Sighting
WSA 99818	Work Station Testing
WSA 99819	Driver Aspect Sequences.
WSA 99820	Design Review Relative to Signalling Standards.
WSA 99821	ATP : Trainborne & Trackside
WSA 99823	SN109 Aspects
WSA 99826	HST Incident Brake Testing
WSA 99827	HST Wheel Slide Protection System Testing.
WSA 99828	HST Door Tests.
WSA 99829	Brake System Investigation: Unit 161 115
WSA 99830	Class 165 WSP Investigation.
WSA 99831	Class 165 Door Examination.
WSA 99832	Structural Investigation. Task 1: Accident Structural Reconstruction. Part A.
WSA 99833	Ladbroke Grove - Structural Investigation. Task 2: Structural Inspection. Progress Report. (Superseded by WSA 99872)
WSA 99834	Structural Investigation. Task 3: Performance Assessment Progress Report (Superseded by WSA 99835)
WSA 99835	Structural Investigation. Task 3: Performance Assessment Progress Report 2. (Superseded by WSA 99873)
WSA 99870	Signaller's Actions
WSA 99871	Train Data Recorder Interpretation (Issue 2)
WSA 99872	Structural Investigation: Task 2: Structural Inspection: Final Report
WSA 99873	Structural Investigation Task 3: Performance Assessment: Final Report
HSL EX/03/2000	Examination of the Diesel Fuels

Report Number	Title
HSL EX/00/08	Examination of Post Fire Residues
HSL ERG/00/05	The Potential for Driver Error
HSL ERG/00/06	Issues of Passenger Egress
HSL ERG/00/07	Slough IECC Signal Box
HSL FR/00/06	Assessment of Fire Developments - Interim Report (Superseded by HSL FR/00/14
HSL FR/00/14	Assessment of Fire Developments
HSL CI/00/04	Examination of the Doors on the High-speed train.
HSL EC/00/19	Examination of Ignition Sources.
HSL EC/00/23	Evaluation of Witness Statements
HSL EC/00/33	Evaluation of Witness Statements with respect to injuries.
HSL FE/00/02	Assessment of bogie & wheelset detachment from vehicles.
HSL FE/00/03	Vehicle Crash Dynamics
HSL FE/00/04	Assessment of vehicle internal fixtures & fittings.
HSL FE/00/07	Review of the Impact Point
HSL MM/00/05	Priority 1 fracture surface examinations
HSL MM/00/08	Priority 2 fracture surface examinations and mechanical properties results
AEA RR-TRS-99-210	Structural Assessment of the Vehicles involved.
AEA RR-TRS-99-239 (Issue 2)	Report into the recorded evidence and the mechanics of the collision.

Glossary

ARS	Automatic Route Setting
ATOC	Association of Train Operators
ATP	Automatic Train Protection
AWS	Automatic Warning System
BTP	British Transport Police
CPS	Crown Prosecution Service
DRA	Driver Reminder Appliance
HMRI	Her Majesty's Railway Inspectorate
HSC	Health & Safety Commission
HSE	Health & Safety Executive
HSL	Health and Safety Laboratory (an agency of HSE)
HSW Act	Health and Safety at Work etc. Act 1974
IECC	Integrated Electronic Control Centre
LGRI	Ladbroke Grove Rail Inquiry
RITC	Rail Industry Training Council
SPAD	Signal Passed at Danger
SSI	Solid State Interlocking
TOC	Train Operating Company
TPWS	Train Protection and Warning System
VDU	Visual Display Unit
WSP	Wheel Slide Protection

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