Formal Incident Investigation

Fracture of the longitudinal beam on the 96 tube stock

Stratford Market Depot

17th October 2019

HSE Info Exchange Reference Number: 106241

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V10.0	19th February 2021

Contents

Executive Summary

Transport for London ("TfL") conducts Formal Investigations into the most serious incidents that occur across its transport network. These investigations are undertaken by trained investigators in accordance with approved procedures. The outcomes of these investigations allow TfL to understand the cause of any such incident and implement suitable action to prevent reoccurrence.

On 17th October 2019, fractures were identified on the longitudinal beams of the coupling system on a Jubilee Line train during a routine B Exam at Stratford Market Depot. The fractures were significant enough to warrant immediate escalation and checking of other trains in the depot. When it became clear the problem was not limited to one train, the findings were escalated to the LU Senior Leadership Team which stood up the LU Major Incident Command Group on the evening of 17th October in response.

The Jubilee Line service was withdrawn in a controlled way on the evening of 17th October 2019 and criteria were established to categorise the fractures and determine severity. After trains were withdrawn from service, only those trains which had been inspected and deemed fit for service (in context of the safety of our customers and workforce) were allowed enter service from 18th October 2019.

On 18th October 2019 letters of assurance from the TfL Director of Engineering, Head of Health, Safety & Environment LU, and the Director of Asset Operations were circulated, along with the submission of a Case for Continued Safe Operation (CCSO) from the TfL Director of Engineering.

Over the following days and weeks, a more detailed examination was undertaken and ultimately identified 58 inner longitudinal beams with fractures on 44 out of 441 cars. Ten of these fractures were deemed Category 1 (most severe) and withdrawn from service until repair could be undertaken.

The interim Formal Investigation Report (FIR) report concluded that the response to the incident was measured and proportionate to the safety risks posed. This is evidenced in the interim report through comparison of the incident management to proven and established protocols, Engineering standards and guidance, application of subject matter expert knowledge, and external review.

The Jubilee Line 1996 Tube Stock (96TS) was introduced in 1997 and initially made up of two 3-car units but designed to accept an additional trailer car to increase capacity.

The 7th Car Project was implemented by Tube Lines in 2005/2006 and an additional Special Trailer car (ST) was added along with four additional trains:

- L14 project: 1997, initial 6-car design
- L17 project: 2005, addition of a 7th car + 4 new trains
- L19 project: 2011, introduction of ATO

The Jubilee Line fleet is currently made up of 63 7-car trains, totalling 441 cars. The insertion of an extra car was undertaken to increase capacity and meet growing passenger demand.

The FIR investigation has identified two root causes:

1. There were failings in the initial design
2. Misconceptions and assumptions were made about the quality and robustness of the initial design which meant that risks associated with subsequent modification were not identified or fully understood

The investigation into the Jubilee Line carbody longitudinal beam fractures completed by TfL Engineering provides further detail on these root causes which resulted in a low fatigue life on the carbody longitude causing cracks to occur:

A. Inadequate consideration of loadcase requirements to demonstrate "fitness for purpose" above those specified as a minimum by the customer in both the original build and the later capacity expansion projects resulting in a product with a short fatigue life.

A loadcase defines how load patterns are applied to a structure to enable it to be checked for strength and serviceability.

[redacted]

[redacted]

B. **Inadequate reassessment of key design changes both in the original design approval and the later capacity expansion projects to determine their impact on other critical components leading to substantial reductions in the carbody fatigue life.**

A Finite Element Analysis (FEA) enables engineers to predict how components may behave under certain conditions.

In the case of the 96TS, there were design changes between initial concept and manufacture, and these changes were not reflected in the FEA leading to it being an inaccurate assessment i.e. the FEA produced lower values than reality. Having an inaccurate FEA meant that the areas of highest stress were not identified as being of concern, consequently these high stress areas at the coupler support bracket interface were omitted from the subsequent carbody strain gauge testing.

The subsequent projects (addition of the 7th car in particular) did not fully question the impact of the changes they were making and worked on the principal that the design has already been proven.

C. **Inadequate consideration of manufacturing limitations in the design of critical bolted interfaces and failure to control manufacture to the set requirements leading to locked in static stress and poor transfer of dynamic loads.**

The initial design did not adequately consider manufacturing limitations or put in adequate controls during build; the required flatness at the longitude to coupler support bracket bolt interface was not achieved which lead to load transfer from the longitude web as per the design concept to its flange. This change resulted in bending of the longitude and redistribution of stress to the rear fixing holes and web/flange radii both of which are the main crack initiation points.

[redacted]

[redacted]

The Northern Line is maintained by Alstom and they are carrying out their own investigations. The outputs of the FIR, engineering investigations and Alstom investigations will be shared to ensure lessons learned are incorporated into future rolling stock designs (Recommendation 5).

1.0 Preface

The purpose of the Formal Investigation is to determine the causes of the incident and to identify any measures necessary to prevent a reoccurrence. The investigation is not to establish blame or liability.

The FIR has investigated the incident response to the Jubilee Line longitudinal beam fractures and the reasons for the fractures.

Recommendations within this report include engineering recommendations following detailed root cause analysis, along with recommendations from the interim report.

2.0 Interim Report

An interim report into this incident was published on 16th December 2019. The interim report included

- Terms of Reference
- A summary of the incident
- A history of the design and purchase of the Jubilee line trains
- Details on the FIR Panel and others who were consulted/involved in the investigation
- An Interim Engineering report into the understanding of the root cause as of 16th December

3.0 Final FIR

One of the recommendations in the interim report was to carry out a detailed engineering investigation into the root cause. The Engineering investigation has been published (Appendix 2)

To understand the full detail of the investigation, three documents need to be considered

- This summary report
- Appendix 1: Interim report
- Engineering report published in July 2020: Appendix 2

4.0 Root Cause

The FIR concludes that there are two root causes:

1. There were failings within the initial design

2. Misconceptions and assumptions were made about the quality and robustness of the initial design which meant that risks associated with subsequent modification were not identified or fully understood

TfL engineering identifies the detail within these root causes:

A. Inadequate consideration of loadcase requirements to demonstrate "fitness for purpose" above those specified as a minimum by the customer in both the original build and the later capacity expansion projects resulting in a product with a short fatigue life.

B. Inadequate reassessment of key design changes both in the original design approval and the later capacity expansion projects to determine their impact on other critical components leading to substantial reductions in the carbody fatigue life.

C. Inadequate consideration of manufacturing limitations in the design of critical bolted interfaces and failure to control manufacture to the set requirements leading to locked in static stress and poor transfer of dynamic loads.

Note: all TfL engineering findings have been independently reviewed by SNC Lavalin specialists.

5.0 Causal Factors

TfL Engineering have further identified the following causal factors:

Causal Factor 1- No Structural Assessment of intercar coupler forces on the carbody completed by the train manufacturer

The loadcases used to validate the original L14 vehicles design were taken directly from the mandatory minimum requirements within the specification and the wider implications of the vehicle's formation with respect in service coupler loadings was not considered within the assessment.

While there was no specific requirement within the specification to complete an assessment of an intercar coupler fatigue loadcase for the carbody, there was a requirement for the contractor to identify and assess loadcases that would be necessary to demonstrate the vehicles design is fit for purpose.

This omission critically resulted in no structural assessment of the carbody with regard to in service loading resulting from accelerating and breaking the mass of the trailer cars and their passengers transferred through the couplers.

Causal Factor 2 – The structural assessment by FEA and static carbody testing had variations to the final design as well as testing omissions which resulted in the underlying structural design weakness not being identified.

The Carbody proof loadcases due to intercar coupler forces were derived from the specification requirements for a light collision [redacted]

The construction of the carbody FEA with relation to coupler geometry and positioning does not represent the final design and is considered to be unconservative. Under the applied proof coupler loadcase stress concentrations were identified in the FEA around the bracket to longitude interface and at the connection of the longitude to the tertiary headstock both positions were some cracks have formed.

During the carbody static testing the opportunity to further investigate the longitude stresses at the coupler interface was missed as no strain gauges were fitted at this location, additionally high test results at the weld between the longitude and tertiary headstock which demonstrated a weld HAZ fail under proof loadings was not identified (corroborated by recent in service testing) and potential concerns around the design missed.

Causal Factor 3 – Failure to reassess the impact of changes to the design [redacted]

[redacted]

[redacted]

Causal Factor 4 - Inadequate consideration of manufacturing limitations [redacted] **failure to control manufacture to the set requirements** [redacted]

The positioning of the coupler support bracket across the headstock / longitude weld is considered a significant risk in maintaining a flat interface due to likely deformation of the both the headstock and longitude when welding, [redacted]

The forces at either end of a coupler will be the same and therefore the same fatigue damage should accumulate on each intermediate end. From this it would be expected that the L14 manufactured cars would have slightly higher level of cracks than the new L17 cars, however this is not the case at either end of the special trailer car or for the 4 additional trains. While the reason has not been fully established there are concerns that the later L17 cars have not been built to the same manufacturing standards as the earlier L14 car which has further reduced their fatigue life.

Causal Factor 5 – No further consideration of the increase in intercar coupler forces was made on the coupler or carbody structure as part of either the L17 (introduction of the Special trailer) or L19 (Introduction of ATO) capacity expansion projects.

The requirement for both a 6 and 7 car train options was present within the original L14 specification and initial designs were progressed to cover both arrangements. With respect to the coupler loadcases this resulted in the crashworthiness calculations being completed for the more onerous 7 car arrangement.

Within the Alstom submissions to support the approval of the additional L17 cars and introduction of ATO (L19) it is clear that there was a general assumption that the coupler system had been designed for a 7-car formation. This is correct with respect to crashworthiness, however as previously discussed at no point was a fatigue assessment of the coupler in-service loads considered in either the six or seven car formations.

Both the L17 and L19 projects' acceptance was based upon demonstrating any variances to the original L14 approval were acceptable. As a fatigue assessment due to the in-service intercar coupler forces was not an original requirement there was no variance and no fatigue assessments were made even though both projects' changes had a negative impact on the coupler forces, particularly the introduction of the special trailer car.

Coupler forces and carbody longitude fatigue life

The impact of the introduction of the special trailer car and ATO can be shown with theoretical calculation of the forces at intercar positions for the L14, L17 and L19 arrangements below, (all driving cars motored, tare condition), 95TS is added for reference.

	6 car		7car	
Dates		~1998 to	~2006 to	~2012 -
Stock / Project	(95TS)	(96TS) L14	(96TS) L17	(96TS) L19
Acceleration (m/s^2)	1.3	1.12	0.98	1.2
Maximum Force kN	**15.47**	**13.328**	**27.02**	**33.09**
Coupler location	UNDM / T	UNDM / T	UNDM / SpT	UNDM / SpT
% increase	-	-	**103%**	**22%**

As can be seen the introduction of the special trailer car (reducing one unit to only 50% motored) had the most significant effect, more than doubling forces even with a reduction in the rate of acceleration. The forces are further increased by up to 22% on the L19 project with the increase in the rate of acceleration i.e. approximately 2.5 times higher than those associated with the original 6 car formation. The relationship between load range and stress range is linear but the relationship between fatigue life and load or stress range is not. A doubling of load range will reduce fatigue life by a factor of at least 8.

Additionally, when motor cars accelerate through section gaps power is lost and they no longer provide traction to the train, this results in a further increase in coupler forces as the remaining motor cars compensate. While this occurs with both six and seven car formations, the additional mass of the special trailer car increases the peak coupler force to around 90kN at the UNDM / Special trailer coupler under the 2019 service conditions.

To determine the impact of these changes on the life of the carbody longitude, fatigue life assessments were completed at a number of intercar positions as well as deriving likely values for other formation and cracked locations.

As the relationship between stress and fatigue damage is not linear these increases in coupler forces due to the introduction of the special trailer (and to a lesser extent with the introduction of ATO) have a disproportionate impact on fatigue life and the introduction of these capacity increase project on the 96TS fleet is the main reason why widespread cracks are being found on the Jubilee Line and not the Northern Line at this time.

A total of 6 in service strain gauge tests were completed as part of this investigation in a number of different scenarios, such as through peak service, out of service, manually driven and on a Northern Line vehicle.

While there are a significant number of variables that can affect fatigue life in this arrangement such as inter-car position and build quality it is considered that the Special trailer (D end) under 2019 service duty has a fatigue life in the region of 2.25 years (meaning 2.3% of the population would initiate cracks in this time although they may not be detectable under the current inspection process) according to the fatigue analysis methodology provided in BS 8118 “Structural use of Aluminium”.

An out of service strain gauge test was completed at the UNDM / Trailer position on the Northern Line which had a calculated fatigue life of 11 years. While there are a number of differences between the fleets which would impact fatigue life it is considered likely that the original 96TS in its original six car formation would have a similar magnitude fatigue life (under the current 2019 service duty) and would not have achieved the L14 specification 36 year minimum requirement.

Observation

While not considered a key factor in the formation of fatigue cracks significant concerns were identified with the reliability and underlying functionality of the coupler release mechanism and its ability to always function correctly under collision conditions, CCSO 397 was raised to control the condition while the correct resolutions are identified.

Lastly, the 96TS drawbars and auto-couplers are similar in design to those used on several other LU stocks and are a well proven design, although it is not known to what loadcases they were assessed against. The forces being transferred by these coupler components on the 96TS are higher than recently measured on other stocks and therefore a potential to have a reduced fatigue life.

6.0 Root Cause Analysis

[redacted]

7.0 Recommendations – Interim report

To understand the full detail of the investigation, three documents need to be considered

- This Final FIR
- The FIR Interim Report
- Engineering report published in July 2020: Appendix 2

The content of the interim report still stands with regard to findings (particularly regarding the immediate management of the incident).

However, for ease of tracking, the recommendations made in the interim FIR have been included in this report along with an update.

The recommendations below now supersede those made in the interim report.

Recommendation 1		Update
Purpose	To establish the root cause from an Engineering perspective.	
Action	Complete the investigation into the Engineering and technical root cause.	
Action Owner	Nigel Tate, Head of Rolling Stock LU Engineering	
Action Target Date	31st May 2020	Closed
Validation	Final FIR presented to DRACCT	
Validator	Graham Neil, Head of Profession Vehicles	
Validation Target Date	12th July 2020	Amended: 31st January 2021

Recommendation 2		Update
Purpose	To ensure monitoring of the risk of longitudinal beam fractures continues for both the Northern and Jubilee Line stock.	
Action	Update the TMR to reflect the recommended monitoring and maintenance as determined by TfL engineering via the Jubilee Line CCSO and the Northern Line PST. This can be achieved by building Maintenance Scheduled Tasks (MSTs) into the TMR.	
Action Owner	Lee Milledge, Fleet Manager Jubilee Line Richard Thomson, Head of Fleet, Northern line	
Action Target Date	28th February 2020	Closed for Jubilee Line
	28th February 2020	Extension granted to 30th June 2021 for Northern Line
Validation	Review maintenance records to provide evidence of inspection of the longitudinal beams as per the TMR.	
Validator	Graham Neil, Head of Profession Vehicles	
Validation Target Date	30th June 2020	Closed for Jubilee Line
		8 weeks post action close out

Recommendation 3		Update
Purpose	To ensure monitoring of the risk of longitudinal beam fractures continues for the life of both the Northern and Jubilee Line stock.	
Action	TfL Engineering to determine frequency of inspection required for the life of the Jubilee and Northern Line fleets once the technical root cause has been investigated.	
Action Owner	Nigel Tate, Head of LU Rolling Stock Engineering	
Action Target	TBC final FIR – the inspection regime is currently determined by the CCSO. Once repairs and investigation have been	Closed – Jubilee Line inspection is

Date	completed this will enable a risk based approach to be employed to determine monitoring regimes.	captured in the TMR. Northern Line action superseded by Recommendation 12B
Validation	Review maintenance documentation - inspection regime will be proportionate to the level of risk with new fractures being identified before they reach Category 1 stage.	
Validator	Graham Neil, Head of Profession Vehicles	
Validation Target Date	12 weeks post action date	Closed

Recommendation 4		
Purpose	To reduce the risk of issues on other fleets not being picked up in routine inspections.	
Action	A) Once the root cause has been established, TfL Engineering to identify at risk lines which may have design issues due to being designed and built in a time when the technology available was less sophisticated than today. B) Design maintenance/monitoring regimes for at risk lines. Draw on industry knowledge outside LU to determine a way to identify issues that may not form part of routine inspections e.g. zonal checks from the aviation industry.	
Action Owner	Nigel Tate, Head of LU Rolling Stock Engineering	
Action Target Date	Action target date to be set in final FIR once root cause has been established.	Closed and superseded by Recommendation 11, 14 and 16
Validation	Review monitoring plans for lines which may be considered as being at risk.	
Validator	Graham Neil, Head of Profession Vehicles	

Validation Target Date	6 weeks post implementation of action 4B	Superseded

Recommendation 5		Update
Purpose	To ensure the actions identified from the CCSO which are subsequently made into MSTs follow a robust process across LU Fleet.	
Action	A) Review process for the ongoing interaction between engineering and maintenance in terms of the CCSO, MSTs and TMR. B) Update and implement process	
Action Owner	Nigel Tate, Head of LU Rolling Stock Engineering	
Action Target Date	A) 31st January 2020	Closed
	B) TBC following completion of action 5A	31/03/21 (Action 5b will be closed by the update of RS Standard S2180 Version A7 (current version is A6) – estimated around March 2021)
Validation	Process should ensure that if a Fleet Manager with no prior knowledge of the CCSO reviewed the TMR, it would be clear why the inspection regime was in place.	
Validator	Graham Neil, Head of Profession Vehicles	
Validation Target Date	8 weeks post implementation of action 5B	

Recommendation 6		Update
Purpose	To ensure fleet maintenance record keeping is robust.	
Action	Raise Work Orders relating to this incident and repairs retrospectively on Maximo for the once round check to ensure a digital copy is available.	

Action Owner	Lee Milledge, Jubilee Line Fleet Manager	Closed
Action Target Date	01st April 2020	
Validation	To provide assurance that an accurate digital log is kept for future auditing.	
Validator	Paul Downham, Acting Head of Fleet	
Validation Target Date	30th April 2020	Closed

Recommendation 7		Update
Purpose	To ensure that decisions are correctly recorded as soon as possible to reflect the rationale for that course of action. This will facilitate the ongoing effective management of the incident and enable the correct level of scrutiny and review.	
Action	Review the approach for logging decision making and introduce where required improvements to incident management	
Action Owner	Tim Scott, Resilience Strategy Manager	
Action Target Date	31st March 2020	Closed
Validation	Review implementation of any changes post incident to ensure effectiveness.	
Validator	Richard Jones, Head of Network Delivery	
Validation Target Date	31st May 2020	Closed

Recommendation 8		Update
Purpose	To reduce the risk of human error when issuing and modifying Work Instructions across LU Fleet.	
Action	Review the process for issuing and modifying Work	

	Instructions to ensure human error is mitigated against.	
Action Owner	Paul Downham, Acting Head of Fleet	
Action Target Date	31st March 2020	Closed
Validation	Assurance to ensure the risk of human error is captured in the sign off process.	
Validator	Graham Neil, Head of Profession Vehicles	
Validation Target Date	30th April 2020	Closed

Recommendation 9 – Reviewing the ABRA and QRA		**Update**
Purpose	To ensure the relevant ABRA and QRA are reviewed and updated to reflect the risk of fractures and potential subsequent derailment across all LU fleets.	
Action	Safety, Health and Environment Specialist Team to agree programme of ABRA/QRA review with TfL Engineering for all tube stocks.	Split into two parts R9a – Review and update of ABRA. Closed R9b – Review and update of QRA
Action Owner	Nigel Tate, Head of LU Rolling Stock Engineering	R9b – Nicola Perrins, Senior Risk and Data Science Manager
Action Target Date	28th February 2020	R9a – closed R9b - 22nd September 2021
Validation	Review programme commenced.	
Validator	Graham Neil, Head of Profession Vehicles	
Validation Target Date	30th June 2020	8 weeks post action completion date

8.0 Additional Recommendations following root cause engineering investigation

To address the scale of works required on the Jubilee Line, a project (JUMP) has been stood up. Rather than addressing actions relating to this project (which are captured within the project requirements) and engineering actions which are tracked within the engineering team, the FIR will seek to provide the following assurance to the business:

Recommendation 10	
Purpose	To provide assurance that the JUMP high-level Project requirements and budgetary provision proposal have considered the recommendations
Action	Ensure high-level project requirements and budgetary provision proposal have considered the following: • the requirement to further mitigate risk of further crack propagation through implementation of a long term solution • ensuring the coupler brackets are capable of transferring load • to limit loading requirements on the future permanent longitudinal repair • the 96TS coupler release system should be replaced to ensure it will always correctly function in a collision scenario and eliminate the current costly maintenance burden on the depot
Action Owner	Howard Taylor – Asset Strategy, TfL Engineering
Action Date	1st March 2021
Validation	Supporting documentation demonstrating alignment with Fleet Asset Strategy and intent to handover project to IDP at Pathway Gate 1
Validator	Graham Neil, Head of Profession Vehicles
Validation Date	6 weeks post action close out

Recommendation 11	
Purpose	To ensure existing standards reflect learning from the FIR
Action	To review and update where agreed relevant standards, namely S1-180 and S2-180, in line with the engineering recommendations detailed in report: 96TS Carbody Longitude Cracks Investigation Summary Report

	Ref: AOS-E-RS-Int-J067-TR_16-No-1007-A1
Action Owner	Nigel Tate, Head of Rolling Stock LU Engineering
Action Target Date	8th July 2021
Validation	Review and approve standards to ensure lessons learned from the SHE and engineering investigations have been appropriately incorporated
Validator	Graham Neil, Head of Profession Vehicles
Validation Target Date	4 weeks post action close out

Recommendation 12	
Purpose	To ensure all underlying risks prior to failure have been considered along with requirements for future monitoring
Action	A) Complete a full carbody finite element analysis of the 96TS bodyshells to determine any other underlying risk prior to failure – and make recommendations B) Seek and obtain formal assurance from the Northern Line Service Provision TT250 contract (PFI contract with Alstom) that all necessary investigations on the 1995TS have been undertaken to determine any underlying risk and what control measures are recommended to manage those risks
Action Owner	A) Paul Downham, Head of Fleet B) Richard Thomson, Northern Line Fleet Manager
Action Target Date	31 March 2022
Validation	Review and accept the assurance provided by the Head of Fleet that underlying risks and monitoring requirements identified have been managed
Validator	Graham Neil, Head of Profession Vehicles
Validation Target Date	8 weeks post action close out

Recommendation 13	
Purpose	To ensure the Northern Line is investigated in further detail in light of the 96TS failures to ensure mitigations can be put in place
Action	To provide assurance to LU that the risks affecting the Northern Line have been investigated and mitigated
Action Owner	Richard Thomson, Northern Line Fleet Manager
Action Target Date	20Th Aug 2021
Validation	Review the assurance provided by the Northern Line Fleet Manager
Validator	Graham Neil, Head of Profession Vehicles
Validation Target Date	8 weeks post action close out

Recommendation 14	
Purpose	To ensure lessons learned are shared for future rolling stock designs
Action	A) The report findings are circulated to all new rolling stock projects e.g. Deep Tube Upgrade, DLR B) The findings of this FIR are distributed to all relevant rolling stock engineers undertaking approval roles. C) Provide assurance that all relevant rolling stock engineers have been made aware of the FIR findings
Action Owner	A), B), C) Claire Maclean, Principal Engineer
Action Target Date	A) 31st Jan 2021 B) 31st Jan 2021 C) 31st March 2021
Validation	A) Once finalised report given, formal acknowledgement to be requested from other projects with new rolling stock B) Check the assurance that all rolling stock engineers have been made aware of the FIR findings C) Review and accept assurance that actions have been completed
Validator	Graham Neil, Head of Profession Vehicles
Validation Target Date	A) 4 weeks post A completion B) 4 weeks post A completion C) 2 weeks post B completion

Recommendation 15	
Purpose	To ensure coupler and drawbar fatigue assessments are completed
Action	A) Complete fatigue assessments of the 96TS auto-coupler and drawbars and review the quality of manufacture at critical locations. Document findings along with recommendations
Action Owner	Nigel Tate, Head of Rolling Stock LU Engineering
Action Target Date	31st Aug 2021
Validation	A) Confirm recommendations from review B) Review and sign off plan C) Check the assurance that the plan identified has been delivered
Validator	Graham Neil, Head of Profession Vehicles
Validation Target Date	6 weeks post action date completion

Recommendation 16	
Purpose	To ensure industry wide practices have been reviewed with regard to inspection and maintenance of components that would not normally be checked routinely
Action	• To review practices in other industries and consider adopting them in TfL in line with ALARP principles • To identify and review at risk lines which may have design issues due to being designed and built in a time when the technology available was less sophisticated than today
Action Owner	Nigel Tate, Head of Rolling Stock LU Engineering
Action Target Date	30th Oct 2021
Validation	Review report with recommendations
Validator	Graham Neil, Head of Profession Vehicles
Validation Target Date	4 weeks post action date

9.0 Appendices

Formal Investigation Panel Members

Name	Title	Organisation
Claire Porter	Head of Transport Systems	TfL
Kate Hagan	Lead Investigator	LU
Kevin Crofts	Independent rolling stock specialist	SNC Lavalin
Claire Maclean	New Stock Engineer	TfL
Steve Whysall	LU Rolling Stock Mechanical Engineering Manager	TfL
Lee Milledge	Jubilee Line Fleet Manager	LU
Marian Kelly	Head of HSE LU	TfL
Steve Cordell	Health, Safety & Environment Manager	TfL
Graham Stanbridge	Health and Safety Representative RMT (Trains)	LU
Martin Bell	Health and Safety Representative ASLEF (Trains)	LU
Christopher Green	Health and Safety Representative RMT (Fleet)	LU
Michael Peralta	Health and Safety Representative UNITE (Fleet)	LU

Appendix 1: Interim FIR Report

Appendix 2: 96TS Carbody Longitude Cracks Investigation Summary Report (Ref: AOS-E-RS-Int-J067-TR_16-No-1007-A1)

Formal Incident Investigation

Interim Report

Fracture of the longitudinal beam on the 96 tube stock

Stratford Market Depot

17th October 2019

HSE Info Exchange Reference Number: 106241

MAYOR OF LONDON

Transport for London

Formal investigation report: interim report

	Name	Title	Organisation
Author	Kate Hagan	Change Delivery Manager	LU
Checked by	Marian Kelly	Head of HSE LU	TfL
Commissioned by	Peter McNaught	LU Director of Asset Operations	LU

Version Number	Date
V11.0	16th December 2019

Formal investigation report: interim report

Contents

Executive Summary

On 17th October 2019, fractures were identified on the longitudinal beams of the coupling system on a Jubilee Line train during a routine B Exam at Stratford Market Depot. The fractures were significant enough to warrant immediate escalation and checking of other trains in the depot. When it became clear the problem was not limited to one train, the findings were escalated to the LU Senior Leadership Team which stood up the LU Major Incident Command Group on the evening of 17th October in response.

The Jubilee Line service was withdrawn in a controlled way on the evening of 17th October 2019 and criteria were established to categorise the fractures and determine severity. After trains were withdrawn from service, only those trains which had been inspected and deemed fit for service (in context of the safety of our customers and workforce) were allowed enter service from 18th October 2019.

On 18th October 2019 letters of assurance from the TfL Director of Engineering, Head of Health, Safety & Environment LU, and the Director of Asset Operations were circulated, along with the submission of a Case for Continued Safe Operation (CCSO) from the TfL Director of Engineering.

Over the following days and weeks, a more detailed examination was undertaken and ultimately identified 58 inner longitudinal beams with fractures on 44 out of 441 cars. Ten of these fractures were deemed Category 1 (most severe) and withdrawn from service until repair could be undertaken.

The interim Formal Investigation Report (FIR) report concludes that the response to the incident was measured and proportionate to the safety risks posed. This is evidenced in the report through comparison of the incident management to proven and established protocols, Engineering standards and guidance, application of subject matter expert knowledge, and external review.

The Engineering investigation is still underway with regard to the technical root cause. There are likely to be several contributing factors, but it can be assumed that the spread of the fractures across the fleet and the propensity for fractures to occur in similar locations on each train indicate issues at initial design and build. Subsequent modifications, particularly the addition of the seventh car, have increased the fracture propagation rate due to increased loading.

The mechanism by which the fractures form has been considered at this stage of the investigation to be due to the push/pull forces on the couplers which are generated during traction and motoring. Comprehensive strain gauge testing has been carried out on the underframe to produce a theoretical analysis of the performance of the train formation during traction and motoring for both a six and seven car design. This testing has confirmed that the fractures are formed and propagate due to forces transferred via the coupling and are unlikely to be influenced by other factors such as track or train borne vibrations. The introduction of the seventh car (Special Trailer) has increased the load on all the couplings in the unit by an average of 60%.

TfL Engineering has concluded that deficiencies in the original design and/or its implementation which led to high stresses in the structural member is likely to be the main mechanism of failure. The failure has been expedited through the increased loading which was introduced as part of the 7th Car Project, the minimal in-service friction braking on the trailer cars and the gapping (part of normal operation where individual motors temporarily loose power supply due to gaps being present in the conductor rails e.g. when travelling over points) of the motor cars during motoring. Deficient conditions of the drawbar arrangement may have further expedited failure and increased fracture growth rate.

With regard to maintenance of the Jubilee line fleet, the area in question is not inspected as part of routine inspection and maintenance. This approach is consistent with the Northern Line fleet inspection and maintenance regime. There is no precedent for failure in this area, and the system was well within the expected design life. The final FIR will address whether, when issues of over-torqueing the bolts at the 2012 overhaul were identified, this should have prompted a review of the system with a view to including inspection of this area on the Train Maintenance Regime (TMR).

NOTE: Northern Line Update: The Northern Line (1995 Tube Stock) trains were visually inspected on the days following fracture identification on the Jubilee Line (both lines have a similar coupling design), with no defects found. Two visual once round checks were carried out, one commenced when the first fracture was identified, then as more information from the Jubilee Line became available and it was clear the defects were not limited to one train, a second more detailed visual inspection was carried out and no fractures were identified. In addition to this, a sample of five trains underwent Non Destructive Testing (NDT) and no issues were found.

The Northern Line couplers are currently part-way through an overhaul programme. As part of that programme, the brackets that attach the couplers to the car body are undergoing NDT (they are removed with the coupler when it is sent for overhaul).

On 5th December 2019, Alstom (who maintain the Northern Line) reported that NDT testing had identified small fractures on some of the brackets which were not visible during the visual inspection. The fractures found on the Northern Line are different from the Jubilee Line issues as they are not on the carbody and the fractures are much smaller. These brackets are different to those found on the Jubilee Line in that they are made of aluminium alloy rather than steel.

Alstom raised their version of a CCSO, a Problem Solving Tool (PST) on 6th December 2019. In addition to this, TfL Engineering also raised a CCSO. At this stage it is not believed that there are direct links between the issues on the Northern Line and the Jubilee Line (although both are likely to be a consequence of push/pull loads through the coupler system). At this early stage the scale of the issues are not yet known; testing and further investigation is underway.

TfL Engineering have provided assurance that the fractures found on the Northern Line brackets do not pose an immediate safety risk. Both the PST and CCSO contain the actions with timescales that are required to monitor, control and resolve the issue.

1.0 Preface

The purpose of the Formal Investigation is to determine the causes of the incident and to identify any measures necessary to prevent a reoccurrence. The investigation is not to establish blame or liability.

The FIR has investigated the incident response to the Jubilee Line longitudinal beam fractures and has started to investigate the reasons for the fractures.

This interim report includes current information on the root cause. The investigation is still underway and, as a result, a detailed Root Cause Analysis has not been included in this interim report.

Recommendations on immediate actions and on completion of the technical report have been included in this interim report. The full and final FIR will be completed and this will determine root cause and lessons learned.

This approach has been taken for this investigation based on the following reasons:

- The investigation of a structural failure which is spread across multiple trains is complex and requires a significant length of time. The investigation will need to begin at the initial design stage of the build and cover all aspects of the fleet life since the trains were first introduced. As a minimum this will involve investigation covering Commercial, Engineering, Maintenance, Assurance, Health and Safety, and external suppliers.
- The Jubilee Line has been built and maintained by various organisations. This included Alstom in the initial design, Tube Lines during the addition of the seventh car and latterly LU. Gathering data and historical records from various sources is time consuming.
- It is estimated that the technical investigation will take a further 6 months. Providing an interim report allows for identification of those areas where actions can be taken immediately and the ability to track those actions. This should ensure the pace of the longer term investigation is maintained.
- Both Engineering and Asset Operations have started to implement a temporary fix and design and are considering the permanent solution. It was identified that this report could serve to identify any immediate actions that need to be undertaken, without moving focus away from managing the structural faults.

NOTE: As per a Freedom of Information Request, FIRs can be viewed in the public domain. Some of the documentation reviewed relates to sensitive information that is TfL and LU restricted. For security purposes, these documents are not included in the appendices as they relate to internal security protocols.

NOTE: All engineering reports listed in the appendix are marked 'DRAFT'. Investigation within engineering is ongoing and these reports may be updated. The engineering/technical root cause is expected to be determined by April/May 2020. The initial areas of investigation are listed in appendix 17.5, these are due to be reported on by the end of January 2020. Depending on the findings of these investigations, it is possible they will identify more engineering areas to explore. Once the technical root cause has been determined (31st May 2020), the Jubilee line fractures and causation will be investigated from a health and safety point of view and a final FIR is expected to be produced by 12th July 2020.

2.0 Terms of Reference

Incident: Fracture of the longitudinal beam on the 1996 Tube Stock (96TS)

Date: 17 October 2019

A formal investigation is commissioned into the identification of a safety issue on some Jubilee line trains. When the issue was identified, all Jubilee line trains were withdrawn from service (in a phased process) on the evening of 17th October for detailed inspections. These inspections and further detailed inspections were carried out over the following days. The LU Major Incident Command Group was established on 17th October to ensure that LU operated a safe railway and to address the issues identified.

The purpose of this investigation is to determine the causes of the incident and to identify any measures necessary to suitably minimise the risk of recurrence (not to establish blame or liability).

The investigation should:

- Establish the sequence of events that led to the incident.
- Identify why the incident occurred in terms of immediate cause, causal factors and root causes.
- Identify any actions already underway to address the root causes.
- Develop reasonably practicable recommendations to address the root causes.
- Consider previous or similar incidents.
- The investigation should address the root causes in relation to the running of a safe railway, but not the long-term engineering solutions to the repairs, which will be subject to a separate assurance process.

The investigation should pay particular attention to:

- Understand the root cause which led to the fractures on the Jubilee line
- Design of the coupling plate (and any other relevant elements of the rolling stock), how it differed from other similar designs on LU rolling stock (e.g. the Northern line) and whether the risk of fracturing was considered during defining of the maintenance regime.
- Learning from other LU rolling stock and other railway organisations in design of the coupling plate for Jubilee line.

- The maintenance regime for the Jubilee line, specifically post introduction of the seventh car, and specifically whether the maintenance regime considered and addressed this risk?
    - If there was a defined maintenance regime, was this maintenance regime delivered?
        - If so, consider why the maintenance regime was not effective (the fractures not picked up)?
        - If not, why not? What was the assurance regime in place for reporting on delivery of planned maintenance?
    - If there was no clear maintenance regime, why not?
- The assurance regime for managing this risk on the Jubilee line rolling stock.
- The response to this risk in ensuring the safe operation of the Jubilee line and the LU network overall, specifically
    - The response on evening of 17 October and in the following days
    - The approach taken after the immediate response, e.g.
        - Was the appropriate inspection regime put in place for these trains?
        - Was appropriate safety assurance put in place (including reporting on this safety assurance to relevant people)?
        - The approach taken in relation to other LU fleet.

The Senior Manager leading the investigation panel is Claire Porter, TfL Engineering, supported by:

- Kate Hagan, Lead investigator, LU
- Kevin Crofts, Independent rolling stock specialist, SNC Lavalin
- Claire Maclean, TfL Engineering – Rolling Stock
- Steve Whysall, TfL Engineering – Rolling Stock
- Lee Milledge, Asset Operations Fleet
- Marian Kelly, Safety, Health & Environment
- Steve Cordell, Safety, Health & Environment
- Graham Stanbridge, Health and Safety Representative RMT (trains)
- Martin Bell, Health and Safety Representative ASLEF (trains)
- Christopher Green, Health and Safety Representative RMT (fleet)
- Michael Peralta, Health and Safety Representative Unite (fleet)

An interim report will be shared with the LU MD and LU Directors by 6 December 2019.

The date for submission of the full investigation report to the Commissioning Director for approval and presented to Directors Risk, Assurance and Change Control Team (DRACCT) for final review and approval will be confirmed by 6 December.

Peter McNaught
Commissioning Director
Director of Asset Operations, London Underground

3.0 Summary of Incident

Time	12:30
Date	17th October 2019
Organisations involved and their business units /departments	TfL Engineering LU Asset Operations LU Major Incident Command Group
Location	Stratford Market Depot
What Happened	During a routine B Exam of 96TS, fractures on the longitudinal beams on both sides of the D End of car 96609.
Consequences	Significant damage to rolling stock. Reduced Jubilee Line service. No injuries sustained.
Potential Consequences	In the event of complete failure of the longitudinal beam, the drawbar and associated equipment would detach from that vehicle this would lead to the vehicles separating (i.e. the train dividing) and potentially derailment from the detached equipment interacting with the track. A derailment could result in injury to the train operator and LU customers.
Incident Report Number	106241
Enforcement Authority Involvement	The Office of Rail and Road (ORR) was informed of the incident and were updated regularly. They informed the Head of HSE LU that they were satisfied with approach being taken. LU will share the interim report with the ORR and will take any feedback from the ORR into consideration in the final report.

4.0 Location of the Incident

Fractures were identified on the 96TS longitudinal beams of the coupling system during a routine B Exam at Stratford Market Depot.

5.0 Weather and Environmental Conditions

Engineering have reviewed the potential effect of seasonal temperature changes and there is no evidence to support the environment being a factor. (See Engineering Report Appendix 18.9 for full report).

6.0 Pre-Incident Details

The Jubilee Line 1996 Tube Stock (96TS) was introduced in 1997 and initially made up of two 3-car units but designed to accept an additional trailer car to increase capacity. The initial fleet was made up of 59 6-car (2 x 3 car units) trains in the following configuration (Figure 1): a Driving Motor (DM), a Trailer (T), and an Uncoupled Driving Motor (UNDM).

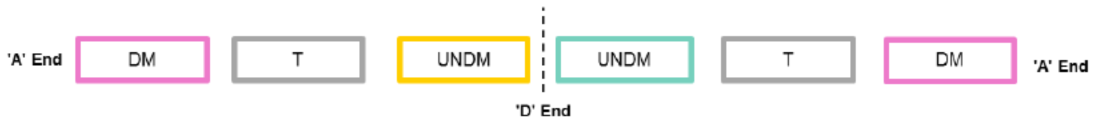


Figure 1: Original Jubilee Line train configuration

The 7th Car Project was implemented by Tube Lines in 2005/2006 and an additional Special Trailer car (ST) was added along with four additional trains (Figure 2). This additional ST car is nominally identical to a standard trailer car but the compressor raft is replaced by a concrete balance weight to permit the same suspension components and settings to be used.

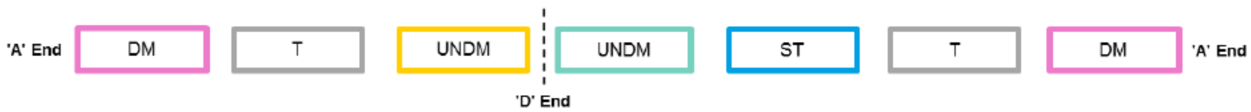
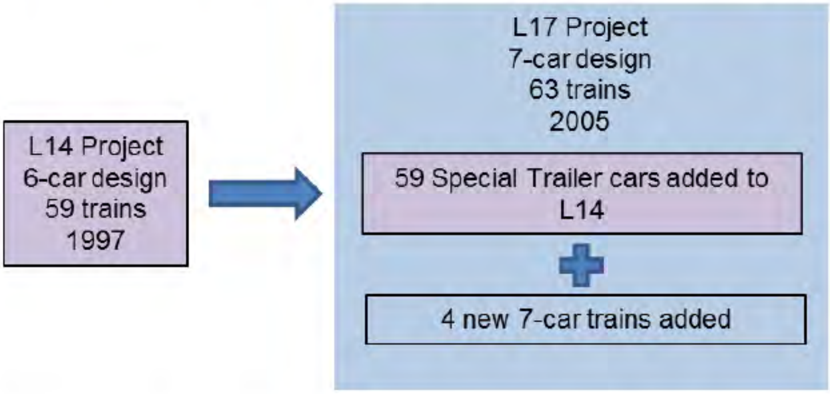


Figure 2: Current Jubilee Line train arrangement

The Alstom project codes are L14 (the initial 59 6-car trains) and L17 (the 59 STs added to the L14 trains, plus 4 new 7-car trains):



The Jubilee Line fleet is currently made up of 63 7-car trains, totalling 441 cars. The insertion of an extra car was undertaken to increase capacity and meet growing passenger demand.

Each car has an A-end and a D-end (see Figure 2) which is connected to the adjacent car through a coupler. The drawgear connects the couplers to the rolling stock.

The drawgear is mounted to both the No. 1 and No.2 inner longitudinal beam and connected by the cross-beam. The assembly is fixed to the longitudinal beam by the cross-beam support bracket (hanger bracket), adjacent to the headstock, and the tie bar support bracket, adjacent to the carbody transverse beam. The longitudinal beam is an extruded aluminium I-beam welded into the floor and headstock (i.e. it forms part of the car underframe), whilst the hanger brackets are steel castings. Ten fixings in total secure each hanger bracket; six through the lower flange of the longitude and four through the lower flange of the headstock, whilst two fixings secure each tie bar support bracket to the longitudinal beam (see Figures 3 & 4).

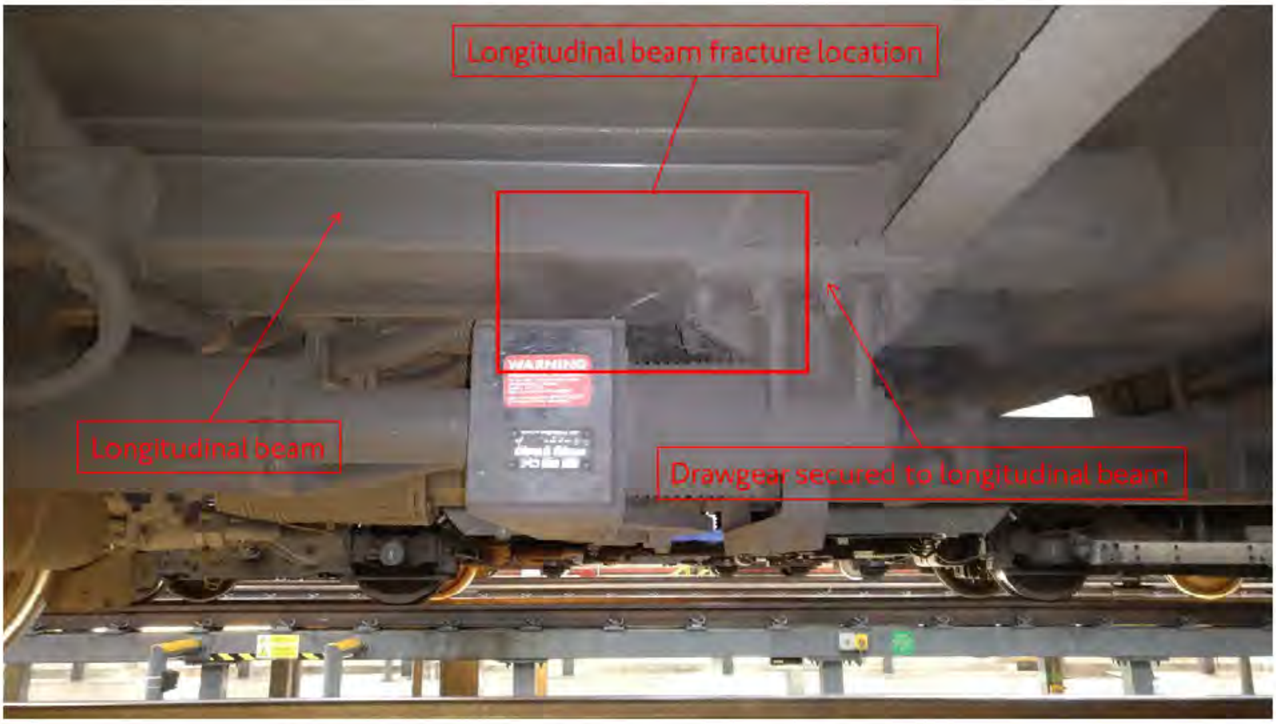


Figure 3: Drawgear secured to the longitudinal beam

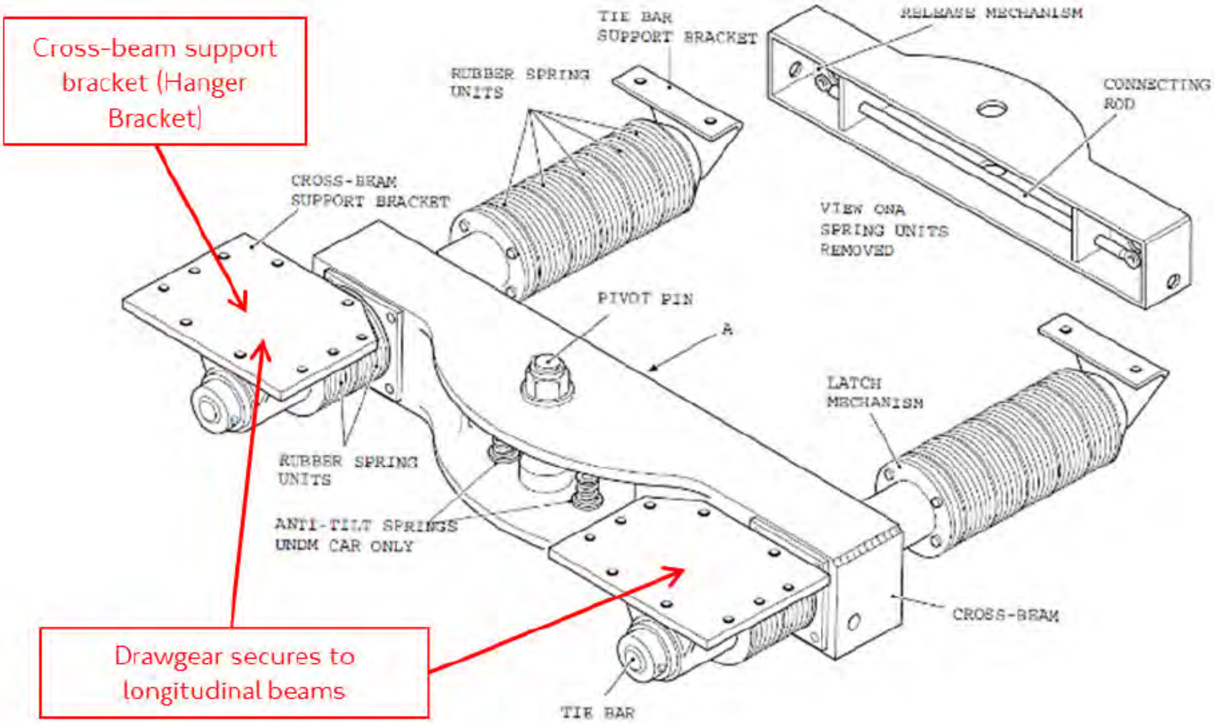


Figure 4: Drawgear general assembly view

In 2011, Automatic Train Operation (ATO) was introduced on the line. Prior to this, the trains were driven manually.

7.0 Incident

On 17th October 2019, during a routine exam at Stratford Market Depot, 96TS car was identified with fractures on the inner longitudinal beams on both the No. 1 and No. 2 sides of the D End of car 96609. (See figures 5 & 6).

Figure 5: Image of car 96609 D End No. 1 side longitudinal beam fractures

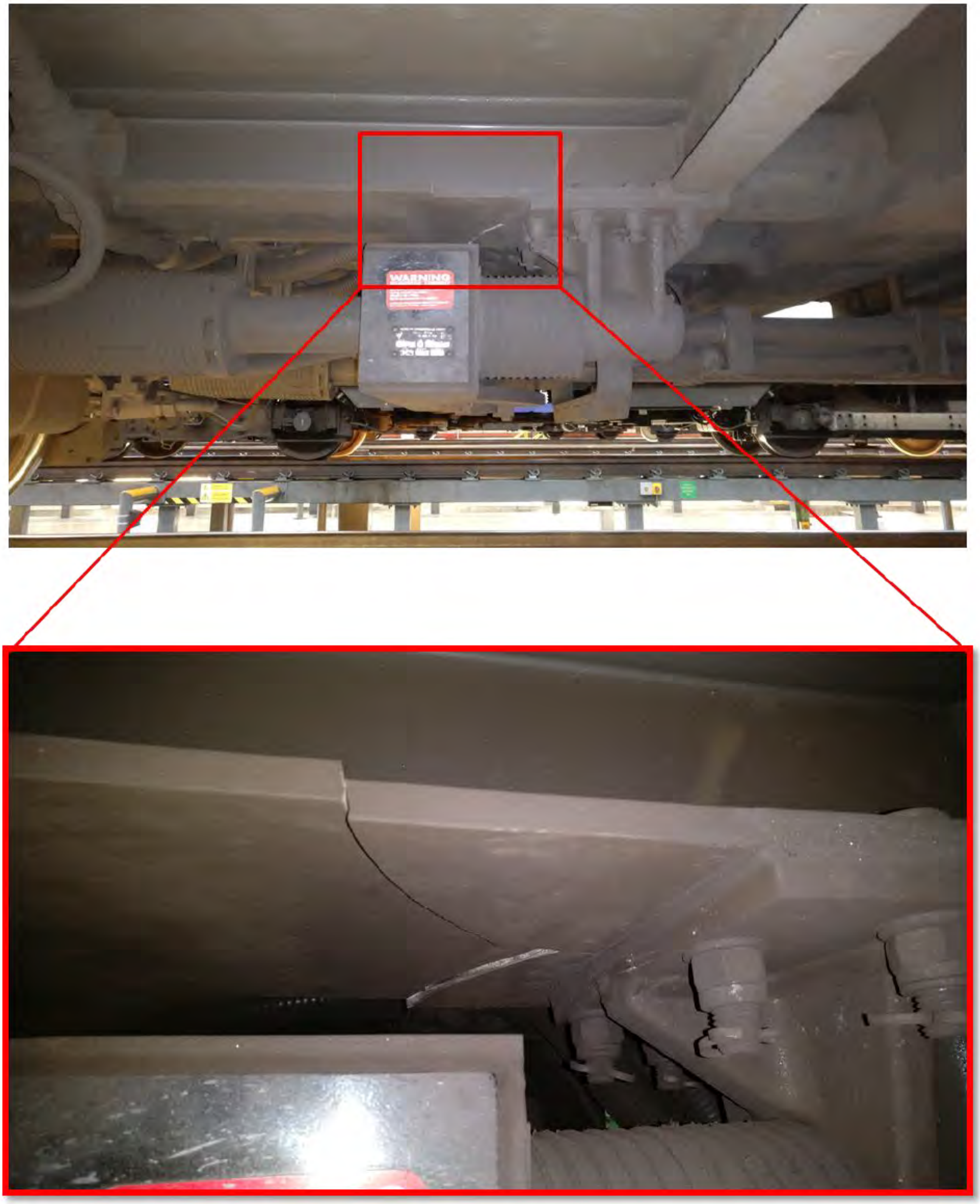


Figure 6: Image of car 96609 D End No. 2 side longitudinal beam fractures

8.0 Incident Timeline

Date and Time	Asset Operations Fleet	TfL Engineering	Major Incident Command Group & Senior Leadership	Internal Communications	External Communications
17th October 2019 12:30	Longitudinal beam fracture identified on car 96609 during B exam at Stratford Market Depot (SMD). Fractures were discovered on both sides of the D End and recorded on the B Exam certificate. Immediately reported to the Asset Operations Fleet Production Manager on duty. Asset Operations Fleet Production Manager raised the required work order in Maximo.				
17th October 2019 13:00	Asset Operations Fleet Production Manager consulted with Fleet Engineering Manager.				
17th October 2019 13:20		LU Rolling Stock (RS) Mechanical Engineering Manager informed by Asset Operations Fleet Engineering Manager. LU Rolling Stock Mechanical Engineering Manager informed Engineering Response Team Leader and Principal Engineer Structures,			
17th October 2019 13:38	Images of fractures sent from the Asset Operations Fleet Manager to the Head of Fleet.				
17th October 2019 14:02		Images for unit 96609 (Special Trailer) received. Identified as F rated defect (see Figure 9) TfL Rolling Stock Mechanical Engineering Manager requested immediate inspection of all trains stopped within the depot carried out by maintenance staff and fleet engineers.			
17th October 2019 14:00	Asset Operations Fleet Manager provided ongoing updates of inspections to the Asset Operations Head of Fleet.				
17th October 2019 14:15		TfL Engineering Response Team Leader attended SMD to view the fractures.			
17th October 2019 14:40		Additional images for second fractured vehicle received. Unit 96055 (Special Trailer) identified as an F rated defect. Third unit identified as fractured in the UNDM unit.			
17th October 2019 14:45		LU RS Mechanical Engineering Manager informed the TfL Engineering New Stock Engineer and discussed appropriate response.			
17th October 2019 15:00	CCSO 394 raised by Asset Operations Trains Maintenance Engineering Manager.				
17th October 2019 15:30	LU RS Mechanical Engineering Manager discussed appropriate response with Head of Fleet.	TfL Director of Engineering, Head of Transport Systems and Head of Methods and Processes informed of fractures			
17th October 2019 15:40	Checks performed on three other units undergoing maintenance at SMD. Fractures identified on two of the three units inspected. Fractures observed in the same position on unit 96055. Alstom (who maintain the Northern Line) informed of fractures on Jubilee line and inspection on the Northern line fleet begins.				
17th October 2019 ~ 16:30	Direct communication between TfL Engineering Head of Transport Systems and Maintenance Engineering. Neasden Depot begin clearing roads to enable further capacity for Jubilee Line inspections	Interim Managing Director London Underground and TfL Engineering appraised of situation. Commissioner appraised of situation.			
17th October 2019 17:00			Decision made to stand up LU Major Incident Command Group (MICG)		
17th October 2019 17:15	Asset Operations Engineering establishes visual checks to be performed commencing on the evening of 17th October 2019.	Checks and categories defined by Principal Engineers (TfL Engineering).			
17th October 2019 17:45			First MICG meeting held at 17:45. Decision made to inspect 10% of rolling stock and make further decision following results. Strategic risks agreed.		
17th October 2019 18:40			ORR informed of situation. ORR content with approach being taken.		

Date and Time	Asset Operations Fleet	TfL Engineering	Major Incident Command Group & Senior Leadership	Internal Communications	External Communications
17th October 2019 20:00	Asset Operations Fleet Shift Operations Manager back on site to oversee the night shift and keep all relevant parties updated with the progress of the fracture checks.	MICG meeting held. Gold control and MICG membership agreed. Categorisation results were received from seven trains: fractures found in four trains. A decision was made to withdraw Jubilee Line from service in a controlled, phased approach. A decision was made to only run trains from start of traffic on 18 October which have passed visual inspection. A plan was implemented to run shuttle service for an event at the O2. Engineering hours were reduced to enable longer traffic hours. A press line was agreed from Interim Managing Director London Underground and TfL Engineering. Other TfL services, Network Rail and Train Operating Companies were apprised of situation.			
17th October 2019 21:00	Conference call with Asset Operations Fleet Manager, Production Manager (AO), Shift Operations Manager (AO), Engineering Manager (AO), Principal Project Engineer TfL Engineering, Interim Managing Director London Underground and TfL Engineering to update on progress and actions.			Head of Line Operations Piccadilly informed the Trade Union (TU) Regional Officers.	
17th October 2019 22:00	Checks began on trains which were withdrawn from service. All couplers inspected (initially thought that the fractures were directly associated with the special trailer cars).		Chair of Trains Health and Safety Council informed the local TU representatives.	Employee Bulletin issued from the Director of Customer Services to all LU: Ramp down of Jubilee Line Services	Customer Communications issued. Communications start with key stakeholders: the Commissioner, Canary Wharf Group.
17th October 2019 23:00	Multiple updates (approx. every 20 minutes) sent by Shift Operations Manager containing the latest spreadsheet of underframe fracture checks carried out.		MICG meeting. Six trains out of fifteen inspected were Category 1 and withdrawn from service There was one Category 2 train, and eight Category 4 trains (details on categorization in Section 9).		
18 October 2019 00:00	Letters of Assurance provided by TfL Director of Engineering and Head of HSE LU.				
18th October 2019 04:30	MICG meeting held. Plans in place to run a reduced morning service.				
18th October 2019 05:00	RIDDOR report submitted. Jubilee Line suspended between Finchley Road and Waterloo.			Customer Communications issued.	
18th October 2019 06:01	Employee Bulletin from the Director of Customer Services to all LU: Significant disruption to Jubilee Line Services				
18th October 2019 06:39	27 Northern Line checks completed, no issues found.		Yammer announcement (using employee bulletin content) to Endeavor Square/Palestra groups		
18th October 2019 07:30	Non-Destructive Testing (NDT) testing begins	MICG meeting. Gold Control (LU Director of Customer Services) made reference to fatigue, action raised to ensure welfare of those involved in MICG.	Stakeholders contacted (time unknown): • The Mayor of London and Deputy Mayor • MPs • Assembly Members • London Boroughs (Harrow, Brent, Westminster, Newham, Tower Hamlets) • Business Improvement Districts • Others: Westfield Stratford, LLDC (Olympic Park), Royal National Orthopaedic Hospital NHS Trust, London First, Confederation of British Industry (CBI), London Chamber of Commerce and Industry (LCCI), The Federation of Small Businesses (FSB), London City Airport, Transport for All, Canary Wharf Group, London TravelWatch		
18th October 2019 08:00	Statement from Director of Customer Services issued to BBC London News. Tweet from TfL which was re-tweeted by the Mayor s Press Office.				
18th October 2019 09:30	Jubilee Line running end-to-end but with severe delays	Revised statement issued from the Director of Customer Services to PA, BBC London, Evening Standard, ITV London, Mail Online and South London Press.			
18th October 2019 13:00	Eight trains stopped due to fractures, thirty-seven trains available. Confirmation that there are fractures are in positions which are not directly associated with the special trailer cars.		Brief report produced by Senior Mechanical Engineer (TfL Engineering) into suspected failure mode, response and timeline.	Ongoing communication with Alstom (Northern Line Maintenance) on findings.	

Formal investigation report: interim report

Date and Time	Asset Operations Fleet	TfL Engineering	Major Incident Command Group & Senior Leadership	Internal Communications	External Communications
18th October 2019 14:30	25% of Northern Line fleet inspected, no fractures found.			Employee Bulletin from the Director of Line Operations and the Director of Customer Services to all Jubilee Line colleagues and LU operational leaders: Update on the Jubilee Line Service	
18th October 2019 16:00		Case for Continued Safe Operation (394 Issue 1) approved to permit the fleet to remain in operation while repairs are designed and implemented. 24 hour on-call Engineering arranged to provide support over the weekend.	MICG meeting. New command structure in place to ensure MICG is focused and has the right membership. Rail Adhesion Train cancelled. Two conference calls held with Trades Unions. Travel Ambassadors utilised to support stations in the morning and evening peak. Continued until 8th November, 332 ambassador shifts utilised in total.		
18th October 2019 17:49				Employee Bulletin from the Director of Customer Services to all LU: Update on the Jubilee Line Services.	
19th October 2019 09:00	Sixty-one out of sixty-three trains checked.	Design for short term repairs approved and implementation commenced on the first train.	Conference call held with MICG panel.		
20th October 2019 09:00	Sixty-one out of sixty-three trains checked. Confirmed that remaining trains would be checked by midday 20th October.		Conference call held with MICG panel.		
20th October 2019	Once round visual inspection of the Jubilee Line completed.				
21st October 2019 05:00	Forty-nine trains offered for service.			LU intranet story published: UPDATE: Jubilee line service disruption.	
21st October 2019 18:45	Assurance letter provided (via email) from Director of Asset Operations that the trains running are safe.	Sign off process for categorisation updated – if new fractures are found, trains are stopped and reviewed and categorised by a Rolling Stock Engineer (TfL Engineering).			
22nd October 2019 09:50	Asset Operations Fleet began stripping down Category 1 trains – found that the bolt was sheared on one longitudinal beam.		Clarity from Head of HSE LU provided on roles and responsibilities of Engineering, Asset Operations and HSE.		
22nd October 2019 16:30		TfL Engineering updated CCSO	MICG conference call – following discovery of fractured bolt, decision made to remove Category 2 trains from service.		
22nd October 2019 22:07				Employee Bulletin from the Director of Line Operations and the Director of Customer Services to all Jubilee Line colleagues and LU operational leaders: Update on the Jubilee Line fleet.	
23rd October 2019		Dedicated SharePoint site set up. Daily flash reporting implemented. Process map for daily and medium-term requirements produced. New approach to engineering assurance implemented – Rolling Stock Mechanical Engineering Manager (TfL Engineering) confirms each morning that the Jubilee is safe to run.		LU intranet story published: UPDATE: Jubilee line services starting to recover. Going Underground newsletter published: Jubilee line update from the Head of Customer Services Jubilee Line and the Head of Line Operations Jubilee Line.	Customer Communications issued.
24th October 2019 12:30	Category 1 repair test trials commence.		Independent review provided by Xanta Limited. Review determined that a competent response is in place and should be allowed to continue .		Update provided to London Assembly Transport Committee Chair and Transport Committee Deputy Chair.
25th October 2019 15:41				Employee Bulletin from the Director of Asset Operations to all Asset Operations – Fleet: Jubilee line fleet – thank you for everything you re doing. LU intranet story published: Jubilee line service disruption: more information on the fleet. Note from the Interim Managing Director London Underground and TfL Engineering to Top 100.	Updated statement from the Director of Customer service issued to The Mirror.
28th October 2019	Northern Line completes once round visual inspection – no fractures found.				
31st October 2019					Customer Communications issued. Update provided to: Canary Wharf Group, London First, CBI, LCCI, FSB, NWEC, London City Airport, Transport for All
1st November 2019			Network Response Plan for reduce Jubilee Line service distributed. Effective from start of traffic 4th November 2019 (schools returning from half term).	Employee Bulletin from the Director of Customer Services to all LU: Thank you. LU/Source intranet story: Jubilee line to be much busier over the coming weeks. Yammer announcement to Endeavor Square/Palestra groups: Jubilee line to be much busier next week.	
4th November 2019	Northern Line commences second round of detailed inspection and approves decision to utilise the ongoing overhaul process to carry out NDT.				
6th November 2019			MICG stood down		

9.0 Immediate Actions Taken

1. Three units undergoing maintenance in the depot were visually inspected and fractures were identified on two of the units.

2. Consultation between TfL Engineering and Asset Operations Engineering determined that a visual 'once round check' be performed commencing on the evening of 17th October 2019. Visual check criteria were implemented to categorise the fractures and the decision was made to withdraw the Jubilee Line trains in a controlled approach. These criteria were defined by TfL Engineering Rolling Stock Engineers) and were established in line with subject matter knowledge on fractures that have affected other fleets and in conjunction with G186 'Assurance of Fractured Rolling Stock Components'. The criteria were established as follows by the Principal Engineer:

> "At each position inspect inner long from above to determine if cracks are present. Pay special attention to the area around the last bolt (circled below). Inspection should be carried out on each inner long and both sides of the inner long web. Any cracks identified should be categorised in line with the below criteria and photographed".

The criteria for categorising the fractures was implemented on the evening of the 17th October 2019 to enable assessment of severity. This risk-based approach designed by TfL Rolling Stock Engineers enabled a limited service to run:

Worst inner long	Run criteria
CATEGORY 1	STOP
CATEGORY 2	Run for 3 days and re-inspect
CATEGORY 3	Run for 7 days and re-inspect
CATEGORY 4	Run for 28 days and re-inspect
Not categorised but concerned	Provide photographs and contact Engineering

Figure 7: Fracture categories

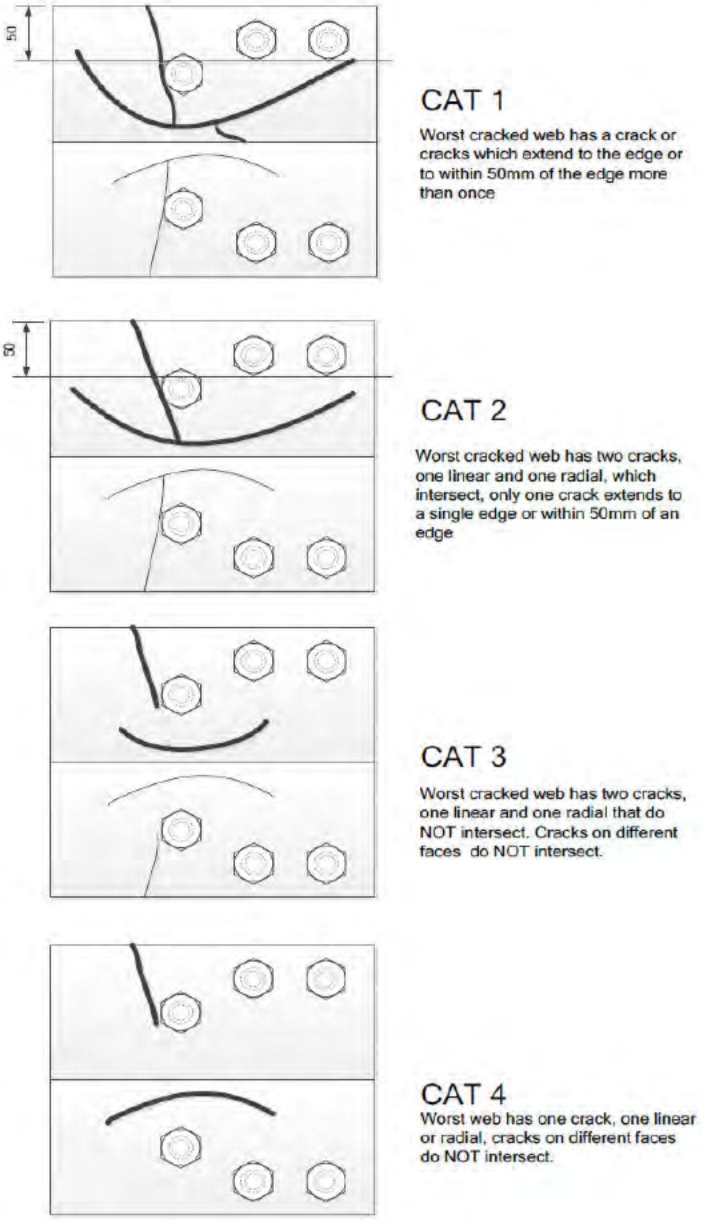


Figure 8: Diagrams of fracture categories

3. When it became apparent that more than one unit was affected, the Northern Line fleet team was informed and they began carrying out visual inspections. This was later followed by a second, more detailed inspection. This immediate action was taken due to similarities in design of the coupling systems on both the Jubilee and Northern Line stock. Both systems were built by Alstom. The Northern Line is still maintained by Alstom whilst the Jubilee Line is maintained by LU.

4. Escalation to the senior leadership team resulted in the decision to stand up the LU Major Incident Command Group (MICG).

5. At the first MICG meeting, the decision was made to inspect 10% of the fleet before making further decisions. This decision was made in conjunction with TfL Senior Engineers and the

MICG. Once it became apparent the whole fleet may be affected, the decision was made to check the entire fleet and timescales for doing this were established. These decisions were made in accordance with S1180 A9 Standard for Rolling Stock (Figure 9), and S2180 A6 Passenger Rolling Stock (Figure 10).

Grade	Hazard Definition	State of asset that grade represents	Action required, if hazard found
F	Major Safety Hazard, asset unfit to use. Circumstances which allowed this fault to develop to be investigated in depth. The investigation shall include checking a sample of other assets of similar design or with similar Maintenance Regime to determine whether the fault is a one-off incident or exists elsewhere.	A major breakdown in asset integrity, either through design deficiencies or ineffective maintenance.	Remove asset from service. Record in detail the defect. Asset not to return to service until defect has been rectified. Report the circumstances to LU using the Rolling Stock Notifiable Incidents process, PR0481.

Figure 9: S1180 A9 Standard for Rolling Stock section 3.3.8.3 Table 4

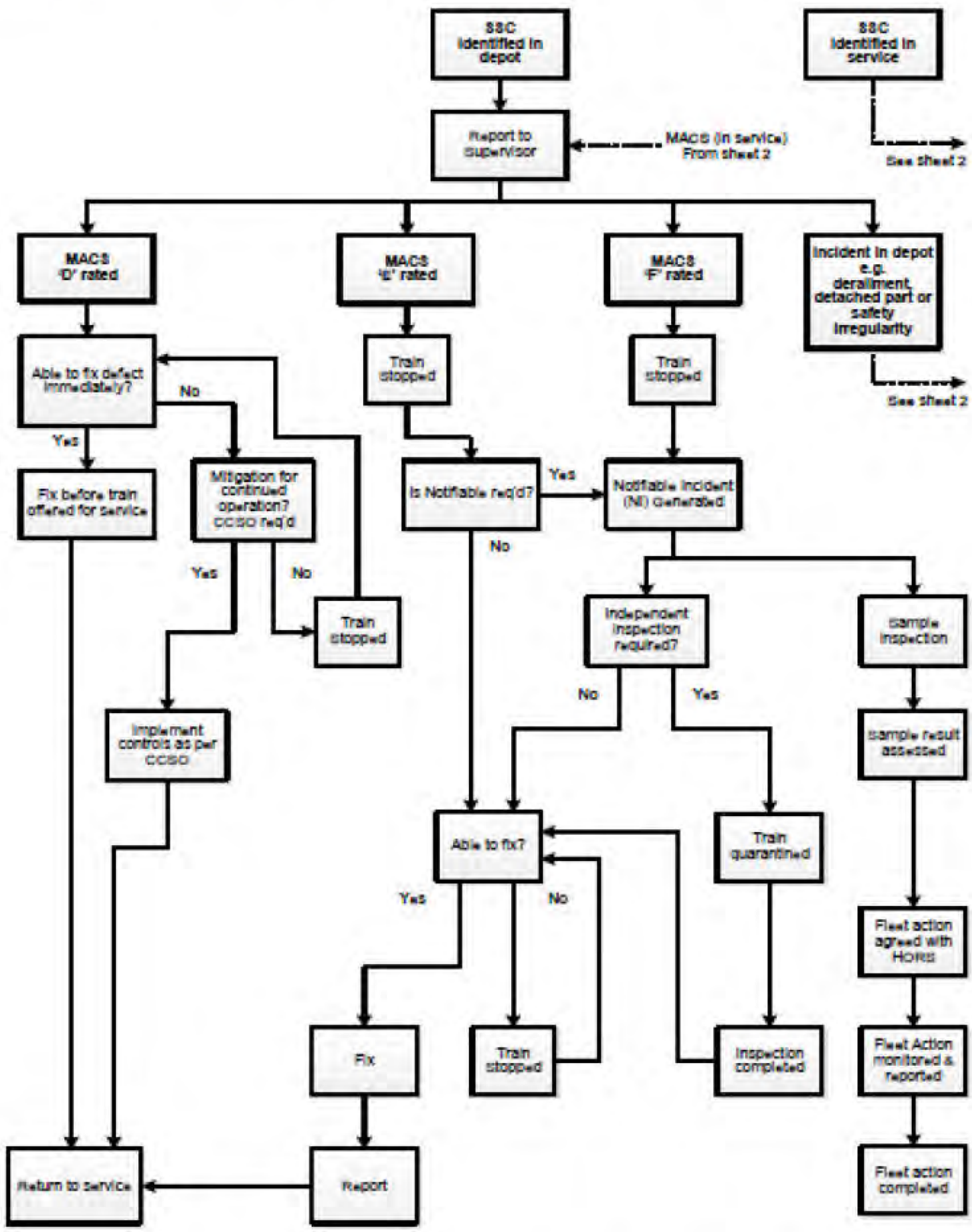


Figure 10: S2180 A6 Passenger Rolling Stock Substandard Condition Process Fig A3.1.11.2 Sheet 1

6. Collaboration with the depot at Neasden allowed some Jubilee Line trains to be inspected there in order to increase the volume of trains that could be checked. The MICG, Engineering and Maintenance teams worked throughout the night and the weekend to manage the situation. TfL Senior Engineers also provided weekend on call cover.

7. As trains were being withdrawn on 17th October 2019, a shuttle service was implemented in order to safely move crowds from an event at the O2 arena. To mitigate further, engineering hours were reduced to allow trains to run later.

8. Key internal and external stakeholders were apprised of the situation including the Office of Rail and Road and the Trade Unions.

9. TfL Surface forms part of the MICG and as such the impact on Surface Transport was monitored through this process. The TfL Surface team was also able to provide operational support to LU by running additional services to support getting customers back from the O2.

10. Communication plans for both internal and external stakeholders were implemented on the evening of 17th October 2019 in accordance with the Employee Communications and Engagement Major Incident Strategy.

11. The decision was made to only return to service those trains which had been visually inspected and deemed safe to run.

12. A Case for Continued Safe Operation (CCSO) was written and approved on 17 October 2019 at 1500 – CCSO 'longitudinal crack' Number 394, Issue 1 (see Document Appendix 17.1).

    As of 6 December 2019, the actions within the CSSO were ongoing and are being tracked to completion by TfL Engineering.

13. On 18th October 2019, the Jubilee Line was running end to end but with severe delays (33 trains were offered for service). There was no significant disruption to Night Tube service.

14. As per the requirements of Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (RIDDOR), a RIDDOR report was submitted to the ORR on 18th October 2019.

15. On 18th October 2019, Non Destructive Testing (NDT) began on the Jubilee Line fleet which provided more accurate analysis than visual inspection alone. This testing was completed by 21st November 2019 and identified 58 inner longitudinal beams with Cat 1 – Cat 4 fractures on 44 out of 441 cars.

16. Letters of assurance were issued by the Head of HSE LU and the TfL Director of Engineering on 18 October 2019 at 0100.

17. A report was issued from TfL Engineering on the suspected failure mode, response and action plans. (See Engineering Report Appendix18.1 for full report).

18. The MICG continued to set strategic objectives as the incident unfolded and put in plans to mitigate the impact on customers whilst keeping safety as the key priority. This included event planning, communication strategies and the utilisation of Travel Ambassadors on LU stations to provide support to stations which were likely to be busier than usual due to the reduction in the Jubilee line train service.

19. Delays continued on the Jubilee Line as trains were withheld for inspection and those with the most severe fractures were removed from service until repairs could be undertaken. Each day, Line Operations were informed of the number of trains that could be offered for service and plans for running a degraded service were implemented.

20. Short term repairs were designed and the Category 1 fractures began undergoing repair on 21st October 2019. These repairs have a fatigue life of 3 years. This means there is a 2.3% probability of a fracture initiating in 3 years. It does not refer to the length of time it could be used before needing to be repaired.

    Long term repairs which will last the lifetime of the fleet are in design stage. The ongoing fracture repair process is out with the scope of the Terms of Reference and will not be detailed in this FIR.

21. On the 22nd October 2019, following disassembly and inspection of the drawgear, a number of M16 bolt fixings within the crossbeam support bracket (see Figure 4) were found to have failed. This prompted a review by TfL Rolling Stock Engineers that resulted in the decision to also stop Category 2 trains from running.

Category Run Criteria		Definition of the Category
Category 1	STOP	Worst cracked web has a crack or cracks which extend to the edge or to within 50mm of the edge more than once
Category 2	STOP	Worst cracked web has two cracks, one linear and one radial, which intersect. Only one crack extends to a single edge or within 50mm of an edge
Category 3	Run for 7 days and re-inspect	Worst cracked web has two cracks, one linear and one radial that do not intersect. Cracks on different faces do not interconnect
Category 4	Run for 28 days and re-inspect	Worst web has one crack, one linear or radial. Cracks on different faces do not intersect.

Figure 11: Amended categorisation of fractures

22. On 22nd October 2019, roles and responsibilities of Engineering, Asset Operations and HSE were defined as follows:

    Engineering: Accountable for providing assurance that the Jubilee Line is safe to run by defining the appropriate inspection/testing regime and responsible for reviewing the information sent to them by Asset Operations.

    Asset Operations: Responsible for delivering the inspection/testing to the standards set by Engineering and stopping any trains in line with those standards. Also responsible for providing data to Engineering.

    HSE: Responsible for overarching LU safety and providing challenge (non-engineering/technical challenge) to the rest of the LU team.

23. By 22nd October 2019, 51 of the 63 trains were running (81% of service capacity).

    As of 6 December 2019, 58 trains were running (92% of service capacity).

24. TfL Engineering sourced an independent review from a Director within Xanta Rail (see Document Appendix 17.2). This was requested to provide an independent view of how the work on containment and rectification of the fracture problem was being managed. This review was carried out on 24th October 2019 and determined that the CSSO represents a state in which the safety risk is As Low As Reasonably Practicable (ALARP):

    "The principal requirement is to contain the problem and establish criteria for continued safe use of the affected vehicles. This has been done as envisaged in G186 and a Case for Continued Safe Operation (CCSO) produced. The CCSO depends upon categorisation of failures according to their severity. The most severe are removed from service until a repair scheme is in place. Vehicles with damage in the less severe categories are allowed to be operated subject to a scaled inspection regime; the more severe the damage the more frequent the inspection. This protects against crack growth reaching the most severe levels originally found.

    Even the most severe damage has not resulted in catastrophic failure, and its removal from service with only less severe damage being present, subject to a scaled inspection regime, underpin the CCSO which is predicated on the absence of unacceptable risk of catastrophic failure. This is a reasonable and supportable conclusion to have reached. It is possible to go further and to state this represents a state in which safety risk is ALARP because;

    - *The amount of effort being applied to contain the problem is consistent with 'reasonable' levels of expenditure defined by DfT Value of Prevented Fatality criteria; there would be no way of spending the sums implied by the VPF criteria to beneficial effect beyond that already being spent; and*
    - *What is being done is self-evidently 'reasonably practicable' and relevant to the problem through its compliance with G186, which is an established and proven response to such problems.*

    Because the approach has categorised failure severities with appropriate response criteria, it also provides an effective response to the need to provide continued service operations; only vehicles that are safe to operate are operated providing the level of service that can be provided. The only alternative is no service."

25. Process maps defining daily reporting requirements (Figure 12) and medium-term change requirements (Figure 13) were implemented along with the production of daily flash reports to update on progress (Appendix 17.6). A SharePoint site was set up which included the change control register and relevant documentation.

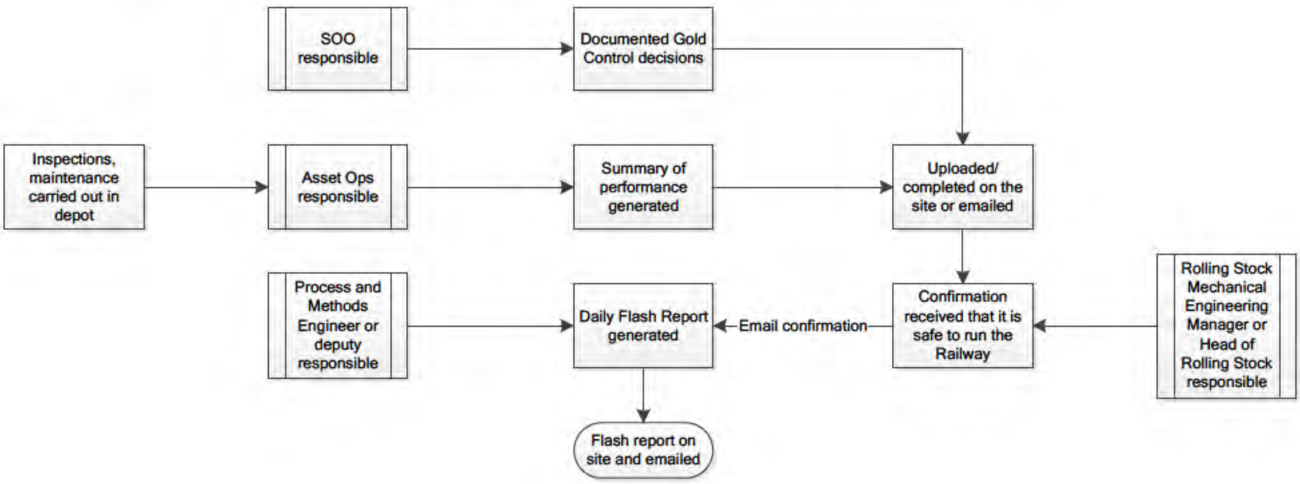


Figure 12: Daily Reporting Requirements

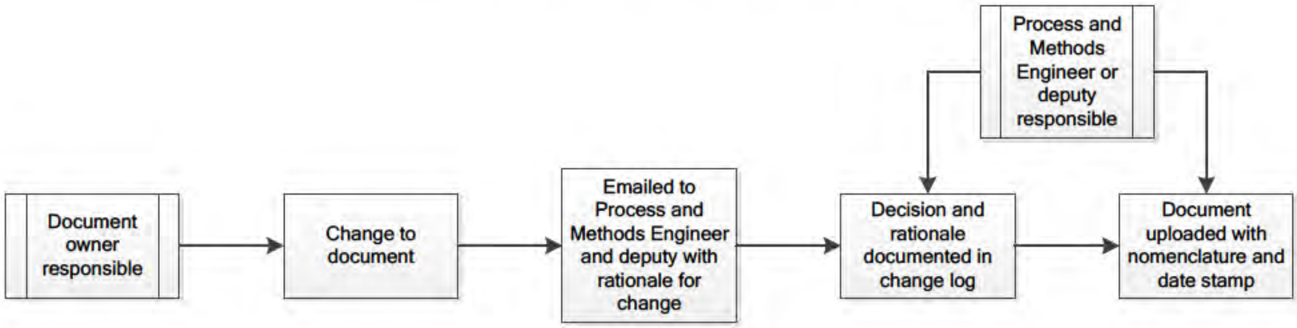


Figure 13: Medium Term Change Requirements

26. The MICG continued to operate and provide strategic decision making until it was stood down on 6th November 2019. From that point on, details on the status of the Jubilee Line fleet were provided on the 08:30 LU conference call and via the Daily Flash Report. When the MICG was stood down, it was agreed that, should there be any issues which required escalation, that this would be done through the 08:30 LU conference call.

27. As of 23rd November 2019, the Northern Line fleet had undergone two rounds of visual inspection and are now (as of 6 December 2019) using the overhaul that is currently underway as an opportunity to undertake more detailed inspection using NDT. To date, no fractures have been identified on the longitudinal beams. However, small fractures have been identified on some brackets (see NOTE in executive summary).

28. NDT was completed on the Jubilee Line stock by 25th November 2019.

In total, 58 fractures were found which affected 44 out of 441 cars (10%).

Category	Total number of fractures
Category 1	10
Category 2	6
Category 3	10
Category 4	32

Figure 14: Total number of fractures found

10.0 Areas, Subjects and Assets Investigated

Ongoing investigation is underway within TfL Engineering and Asset Operations Engineering. A summary of current thinking and exerts from engineering reports is provided below (the full engineering reports produced to date can be viewed in Appendix 18). It should be noted that until investigation is complete, the technical root cause can not be identified. Ongoing investigation areas and detailed list of engineering actions can be viewed in Appendix17.5.

This report covers the following specific areas:

- 10.1 Potential asset failure precursors
    - 10.1.1 Failure of the drawgear bolts
    - 10.1.2 Addition of the seventh car
    - 10.1.3 Fatigue life
    - 10.1.4 Impact of timetable increases
    - 10.1.5 Train manufacture, initial design, build and assurance
- 10.2 Maintenance
- 10.3 Quantative Risk Assessment and Asset Based Risk Assessment
- 10.4 Incident management

10.1 Potential Asset Failure Precursors

10.1.1 Failure of the drawgear bolts

(See Engineering Report Appendix 18.2 for full report)

Part way through the 8-yearly drawgear overhaul in 2012, it was identified that the drawgear bolts were being over torqued. This over tightening occurred due to an error in the work instruction which specified an incorrect torque value for tightening the drawgear mounting bolts. The work instruction specified mounting bolts should be tightened to 310Nm. CCSO TLL-JLF-PPR-16001was produced following identification of the error and specified that the correct torque for the bolts should have been 210Nm. Alstom drawing (201/A/01/BA/041 Rev A) [2] specifies the torque value should be 230Nm.

The mistake was noticed part way through the overhaul process and 114 of the 126 units had already been completed. There is no indication that any record was kept of which units were affected. Tube Lines Ltd commissioned ESR Technology to carry out an investigation into the effects of over-torqued bolts. A report was produced (ESR/UC000258/TRN/049 Issue 1 (MA3309)) [3] which concluded that tightening to 311Nm should not give any concerns. However, the report used incorrect information regarding the structure of the bolted joint. The report assumed that the inner longitudinal beam was made from structural steel rather than aluminium. As a result, the over-torqueing of the drawgear fixing arrangement to 311Nm would cause stresses in the inner longitudinal beam higher than the yield strength of the material. It is possible that this may have been a contributing factor to the rate of fracture initiation within the inner longitudinal beam, by allowing small fractures to occur within the material's crystalline structure. Failed drawgear fixing bolts have been found which appear to show signs consistent with fatigue. Further analysis by 4-Rail (Scientific and Environmental Testing Consultancy) is being completed to fully understand the failure.

Recommendation: The process of issuing and modifying work instructions should be reviewed to ensure it is robust enough to remove the risk of human error.

10.1.2 Addition of the seventh car

(See Engineering Report Appendix 18.3 for full report).

The seventh Special Trailer car (ST) was added to the Jubilee line fleet in 2005/2006 (as described in Section 6). As part of this investigation, the TfL Engineering team considered the location of the fractures in relation to the car coupling.

Figure15 shows the distribution of fractures per coupling. The majority (57%), but not all, of the coupling fractures occurred between the ST and the UNDM. The forces in this area are high because there are two motor cars pushing/pulling the two trailer vehicles.

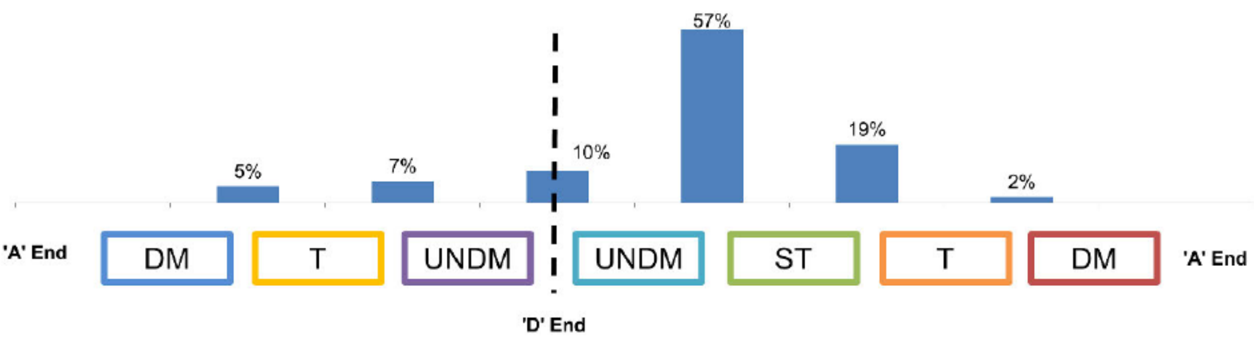


Figure 15: The percentage of fractures for each coupling for a 7-car train

83% of the total number of fractures were discovered on the ST (52%) and the adjacent UNDM (31%) (Figure 16).

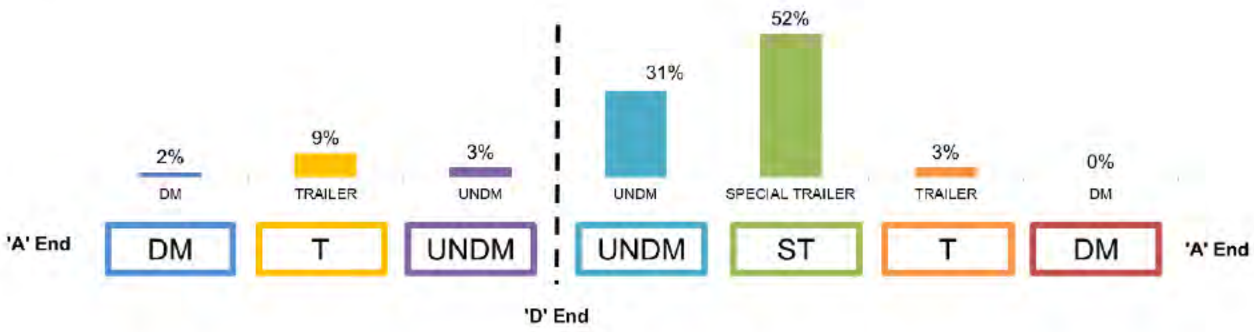


Figure 16: The distribution of fractures per car type for a 7-car train

The ST cars represent 14% of the fleet but exhibit 48% of the cars with fractures discovered. This may partially be due to build quality, but more likely due to the loading conditions at this position within the 7-car train composition.

This analysis suggests that the design phase of the 7th Car Project did not fully appreciate the potential impact of these loading conditions i.e. the high forces generated from the two motor cars pushing/pulling the lighter trailer vehicles (see Figure 17).

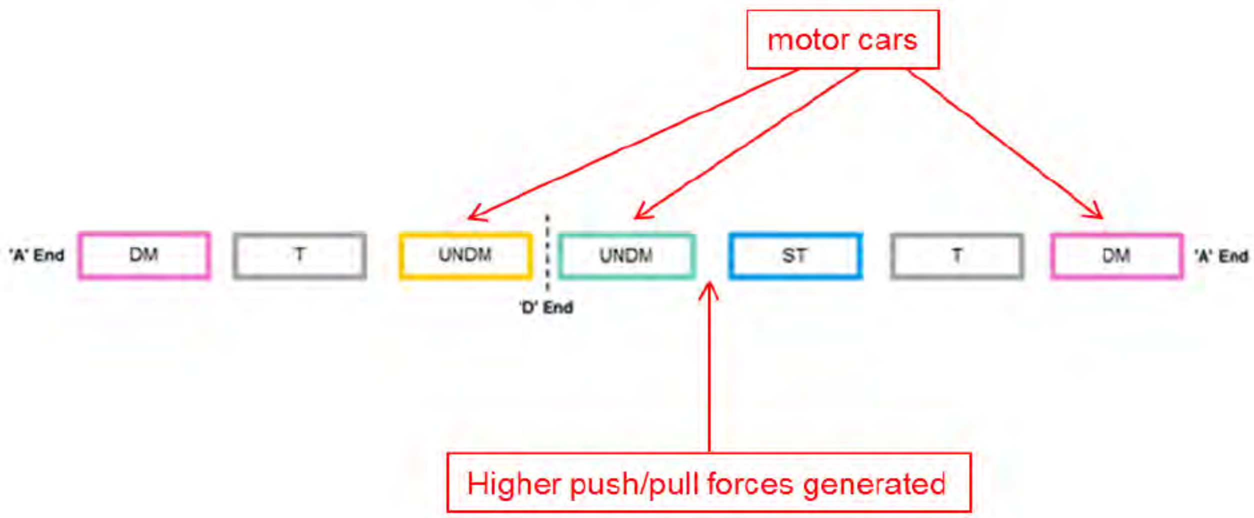


Figure 17: Location of increased push/pull forces

10.1.3 Fatigue life

(See Engineering Report Appendix 18.4 for full report).

The longitudinal beams are part of the structure of the carriage. A bracket is bolted to each of the two inner longitudinal beams on either ends of the carriages. These are attached to the drawgear and transfer buff and draw loads from the drawgear into the car body.

Due to the severity and large population of the fractures found, it is necessary that the underlying failure mechanism is identified. One of the aspects to be considered is whether the typical in-service loading experienced by the longitudinal beam could cause sufficient fatigue damage for the appearance of fractures within the to-date life of the asset and, if this is the case, the factors that influence these service loads. Therefore, a number of instrumented runs were carried out in service and ATO, and out of service and Protected Manual.

Strain gauges were attached to the longitudinal beams on the A end of unit 96685 (ST) which was identified as being intact. A total of 12 gauges (gauge 1 to 12) were attached to the A end of the car on positions around the drawgear bracket as these were the locations where most of the fractures were found.

From stress ranges gathered during the test run and the subsequent fatigue life calculated, it can be concluded that fracture initiation and propagation is mainly a result of the high cyclic stresses on the longitudinal beam as a result of the buff and draw loads transferred through the drawbar and hanger bracket. In some positions on the longitudinal beams these stresses lead to a fatigue life which is much less than the expected operational life of 40 years with some having a fatigue life of less than 10 years. It is also clear that the fatigue life on different ends of a carriage are different because of the variance in loading.

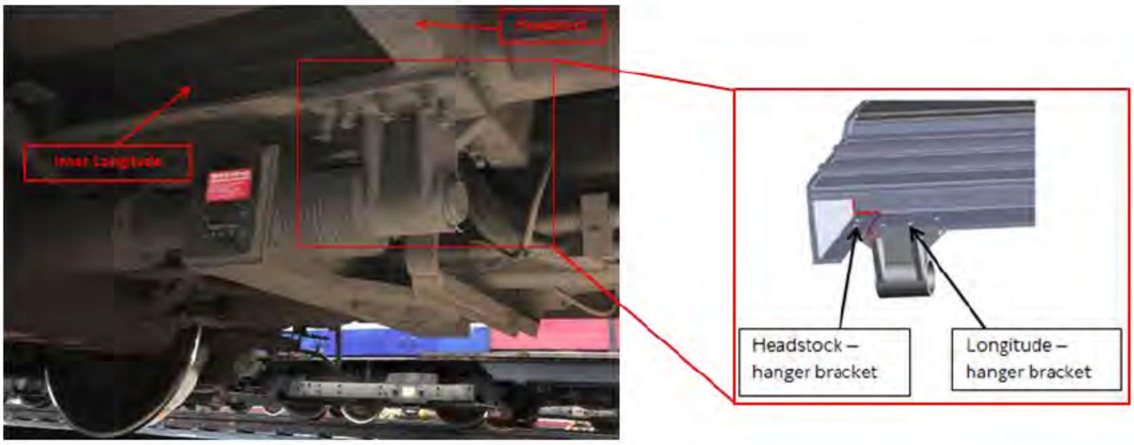


Figure 18: Hanger bracket attaching to headstock and longitudinal beam

10.1.4 Impact of timetable increases

(See Engineering Report Appendix 18.5 for full report)

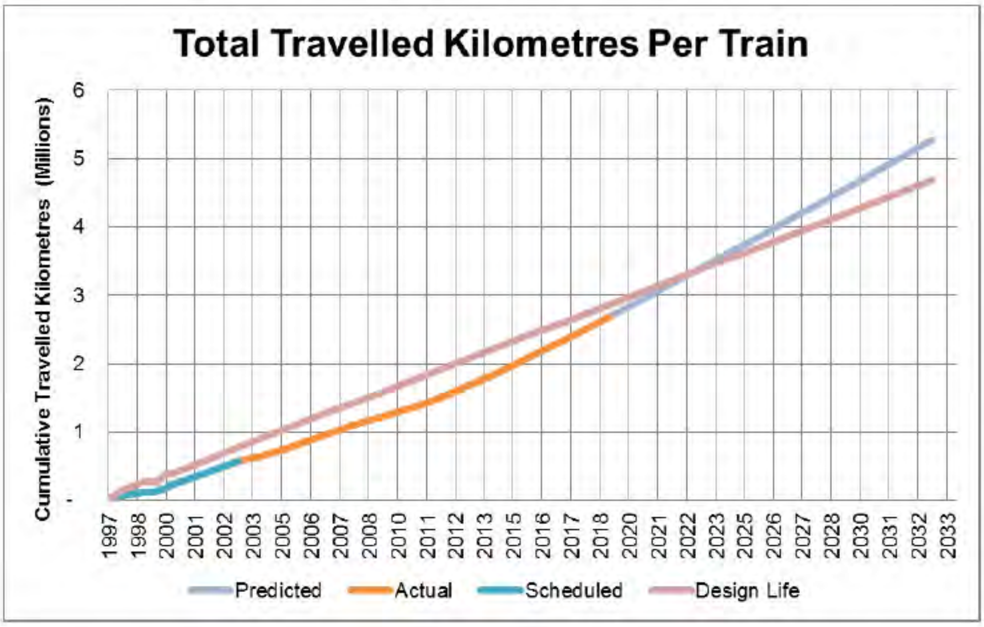


Figure 19: Predicted vs actual cumulative kilometres travelled

The report considered whether changes in passenger loading may have contributed to the failure.

Despite the current similarities between the designed life distances and actual/predicted distances travelled, the graph of extrapolated data shows that the distance the 96TS has travelled will exceed the design life in 2030.

However, as the design life (36 years) has not yet been surpassed, this means that the increase in usage is unlikely to have contributed to the recent spate of inner longitudinal beam failures.

10.1.5 Train manufacture, initial design, build and assurance

(See Engineering Report Appendix 18.6, 18.7, 18.8 and 18.9 for full reports).

10.1.5.1 96 Tube Stock (96TS) drawgear design

The design of the 96TS drawgear assembly and how it is fixed to the inner longitudinal beams is believed to be a significant factor leading to failure of the inner longitudinal beam and inner headstock.

Design Stiffness

The design of the drawgear is such that buff and draw (push and pull) loads are passed through the steel crossbeam support brackets into the aluminium inner longitudinal beams and inner headstock. The inner longitudinal beam and headstock are much less stiff than the support bracket due to material and geometry differences. Typically, abrupt changes in stiffness lead to stress concentration in the more flexible item. These, coupled with the high cyclic loading (repeated fluctuating stress/strain), can lead to fatigue failure. Improving the transition in stiffness, by changing geometry, would likely result in a more robust design, which is less prone to fatigue failure.

Welding Distortion

During manufacture, the inner longitudinal beam is welded to the inner headstock. Both extrusions are made from aluminium, which suffers greatly from post weld distortion, as the material cools down and shrinks. This makes it difficult to achieve a flat surface across the welded joint. The cross beam support bracket is then secured to this uneven surface, and when the fixings are tightened up they pull the less stiff aluminium against the flat steel bracket. This induces stress concentrations in the aluminium extrusion, which are likely to contribute to failure. Additionally, the bolting interface may not behave as designed, and as such the stresses observed in the bolts and surrounding material may increase. This is a likely cause of the fatigue failed bolts found in two drawgear assemblies.

Fixing Arrangement

A. Position of Holes

The positioning of the holes in the crossbeam support bracket does not comply with the minimum edge distance as per Eurocode 3 (BS EN 1993-1-8). The recommended distance is 1.2 times the hole diameter. In this instance the hole diameter is 16mm and the holes positioned closest to the fracture initiation area are only 15mm from the edge of the bracket. This will result in stress concentrations close to the bracket edge, in both the bracket and the aluminium inner longitudinal beam.

B. Washer Position

The original drawgear assembly drawings specify washers to be used between the head of the fixings and the aluminium extrusion. However, at some point (either during original build or at overhaul) the washer was placed between the nut and the steel bracket instead. This would have increased the stress concentration in the aluminium around the bolt head and may have led to initiation of fractures around the bolt holes. In addition, it is known that these fixings were significantly over-torqued during overhaul in 2012, leading to further increase in stress concentrations and likelihood of fracture initiation.

Galvanic Corrosion

Due to the crossbeam support bracket and inner longitudinal being made of dissimilar metals, there is potential for galvanic corrosion. In this instance the aluminium would act as the anode and corrode first. Both the aluminium inner longitudinal and the steel support bracket were given a protective paint coating which acts to electrically separate the components and reduce the likelihood of galvanic corrosion. Minimal evidence of corrosion has been found on the aluminium extrusions and as such this is not considered to be a significant contributor towards failure.

AMPEP Bearings

AMPEP spherical bearings are used at the interface between the coupler and body-mounted crossbeam. The bearing sits within the drawbar and is the primary interface to the coupler pin for both the auto-coupler (between the 3-car and 4-car unit) and the semi-permanent coupler (between adjacent cars).

The AMPEP bearings in the UNDM auto-couplers have been found to be severely worn, this is likely due to the high levels of loading. The high loading is also likely to be a causal factor for the longitudinal fractures.

The AMPEP bearing design used on 96TS is typical of a few other fleets. There is a known issue with this design causing the bearings to degrade due to high loads and reduced clamping. Though degraded AMPEP bearings are not an immediate safety concern, they can lead to increased loads in the drawbar arrangement that could increase damage to the drawgear assembly or surrounding structures. At present it is thought that the worn AMPEP bearings could be a contributor towards the longitudinal beam failures, but this is not considered to be a root cause.

10.1.5.2 96TS drawgear build

It is possible that design flatness parameters were not achieved at the build stage of the 96TS and this contributed to the fatigue of the longitudinal beam and subsequently to the fracture propagation.

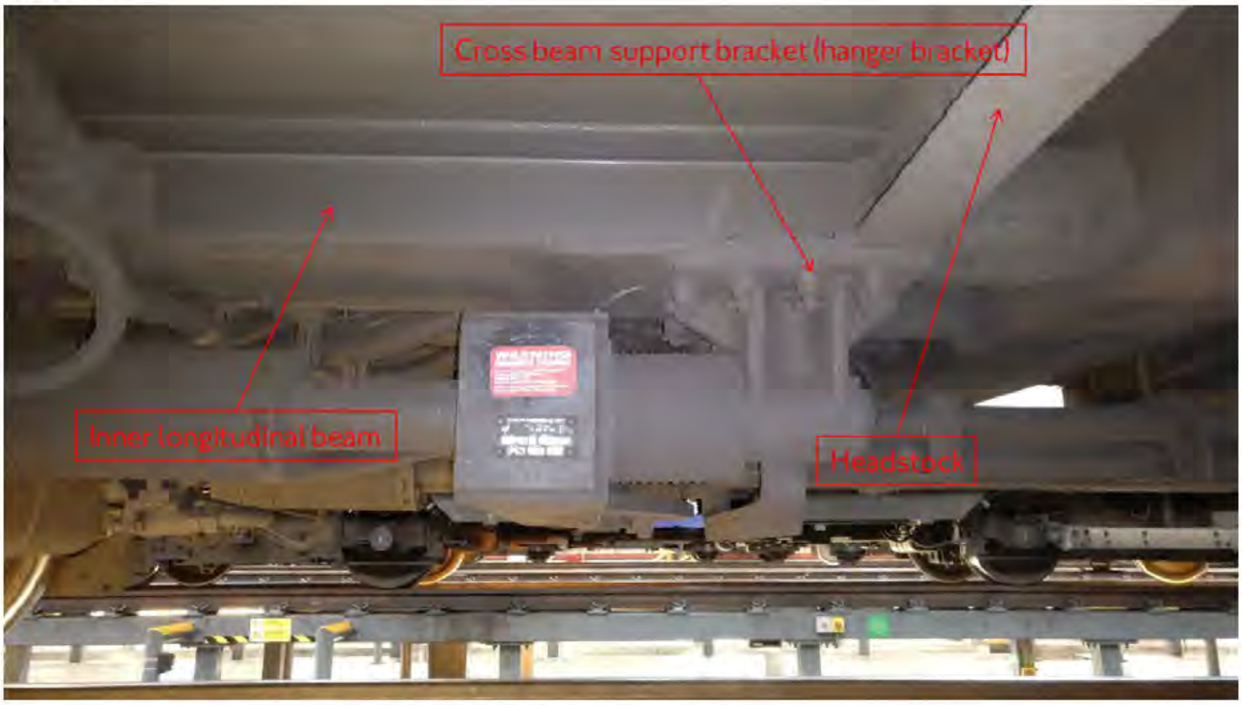


Figure 20: Crossbeam support bracket arrangement

The area where the crossbeam support bracket connects to the underframe represent a complex zone as the welding between the headstock and the inner longitudinal beam generate stresses and distortions. These are key parameters to be controlled at manufacturing stages to ensure adequate quality is obtained. However, from the inspection it was observed that the headstock bottom flange is not horizontal, and therefore not parallel to the lower flange of the inner longitudinal beam, generating a high spot in the area where the two flanges meet. Although grinding was indicated in the drawings to ensure the required flatness is achieved, it is not clear that this was achieved at build.

Evidence gathered from inspection of U9666 U96461 and U96479 shows that the aluminium surfaces obtained by welded joint between the headstock and inner longitudinal beam do not meet the required level of flatness which could lead to the following:

- Localised yielding: high spots within the mating surfaces can generate high stress areas hence yielding of the aluminium face. This has not been seen in the inspected samples.
- Slippage: in extreme scenarios, where contact is not achieved, insufficient clamping force between the inner long and the crossbeam support bracket would let the two parts slipping making the bolts work in shear. This has not been seen in the inspected samples.
- Increased stress on the inner long flanges: during assembly in order to close the gaps the aluminium flange would bend under the bolt preload. Bolts and flange can be overly stressed resulting in possible contributing factor for failure under fatigue cycles.

Rolling stock design sets defined flatness ranges which should be confirmed and monitored, it is not clear that this was achieved in all positions on the 96TS. Additionally, a common precursor of out of flatness measurement is the inclination at which the head stock flange connects to the inner longitudinal beam. It is difficult to achieve the flatness tolerance required if the two components meet at an angle, without removing significant amounts of material. In order to ensure that the mating surfaces contact satisfactorily, it is important that the angle at which inner longitudinal beam and headstock meet is brought to a minimum.

10.2 Maintenance

The maintenance regime for the Jubilee line train is set out in the Train Maintenance Regime (TMR). The TMR is developed by the Asset Operations Fleet team and accepted by the Professional Head of Vehicles, TfL Engineering.

Routine maintenance in the form of a B Exam is carried out every fourteen days, with progressively more detailed inspections being carried out at 28-day, 6-month and 12-month intervals. The longitudinal beam does not form part of these inspections although components in the surrounding area do. Visibility of the longitudinal beam is restricted and the first fracture was only identified through the diligence of the Train Maintainer and at a point where the fracture faces had displaced making the defect more visible. The drawgear had been overhauled in 2012 and was well within the life expectancy of these components.

The Train Maintenance Regime (TMR) details the maintenance requirements for each stock, in the TMR for the Jubilee Line, there is no reference to inspection of the longitudinal beams and this is also the case for the Northern Line TMR. The initial design and build of the 96TS and subsequent modifications did not include inspection of the longitudinal beam as it was not known to be a point of failure risk. The original design and build documents will be reviewed within the final investigation, but to date, an inspection regime of this area was not believed to have been specified at build.

Recommendation: The FIR recommends that as the inner longitudinal beam is now a known point of failure, the TMR for both the Jubilee Line and the Northern Line should be updated to reflect this risk. Consideration should be given to whether this failure mode should be considered for other LU rolling stock, and whether the TMR for those stocks should be reviewed.

Observation: When reviewing the maintenance documentation, the work orders for the visual inspection were only available in hard copy. This is understandable given the time constraints, but the FIR recommends the work orders be uploaded to Maximo in retrospect in order to ensure a digital copy is available.

10.3 Quantative Risk Assessment (QRA) and Asset Based Risk Assessment (ABRA)

The QRA and ABRA for Jubilee Line derailment were reviewed as part of the investigation. The risk of a train being derailed by a detached part is captured in the ABRA which is linked to the QRA. As per the ABRA, the risk of derailment for the Jubilee Line was 0.032 derailments per year which corresponds to a risk of 0.19 fatalities every 10 years. Data in ABRA (Figure 21) demonstrates that, based on existing understanding of the rolling stock design, build and maintenance, a derailment causing twenty fatalities could occur once every 1,562.5 years.

Events per year	Consequences	Probability of a fast derailment leading to fatalities (or not) (%)	Likelihood per year	or once every X years
0.032	Fast Derailment - 2 Fatalities	2	0.0032	312.5
	Fast Derailment - 20 Fatalities	0.4	0.00064	1,562.5
	no fatalities	17.6	0.00282	35.5

Figure 21: ABRA model showing the risk of derailment on the Jubilee Line as the result of a detached part

Recommendation: The FIR recommends that the LU ABRA be updated to reflect the risk of a detached part (resulting from the complete fracture of the longitudinal beam) resulting in a derailment. Following the ABRA update, a programme should be agreed with TfL Engineering to review and update the QRA for the Jubilee and Northern Line.

10.4 Incident Management

The MICG core attendees are Directors and Senior Managers that bring with them a wide range of competence from across the business. The purpose of the MICG is to set strategic objectives in relation to LU's response to a major incident. A strict agenda is followed which is outlined in the LU Major Incident Initial Actions Procedure.

MICG core attendees take part in an annual exercise in which people are given the opportunity to practice the application of those skills they already utilise in their current role but in a major incident may have to apply these under some pressure and in line with a structured process. These exercises simulate the demanding nature of an incident by having time constraints and by receiving no prior warning of the exercise scenario and details.

The MICG process is led by a senior leader from Network Delivery. These people, in addition to the annual exercises, have been trained in incident management, through a formal major incident training course used widely amongst senior leaders in the emergency services and Government agencies.

Additional specialist members can be called to sit on the MICG when a particular competence, skill or knowledge is required. In this case, Senior Rolling Stock Engineers were included in the MICG.

11.0 Human Factors

The FIR considered a range of information during the investigation. The FIR notes that this information came from a wide range of sources including email, interview, reports, standards and guidance, WhatsApp messages, photographs, memory of telephone conversations and anecdotal evidence. The FIR concludes that the assurance of decision-making and accurate accounting of timelines could be improved by keeping a log of activities, decision making and rationale as the incident progresses. Once it became clear the incident involved significant safety concerns and a wide impact on the business, the recording and consolidating of information became more critical.

Recommendation: The LU Resilience Team to review the approach for logging decision making and introduce improvements to incident management where required.

12.0 Similar Incidents

(See Engineering Report Appendix 18.10 for full report)

Swan neck fatigue - primarily affects 72TS: swan necks form part of the carbody underframe and are subjected to the longitudinal forces from the coupler. Historically the swan necks have been prone to fatigue cracking, generated by buff and draw loading as each car in the train accelerates and brakes.

Semi-permanent coupler bracket cracks – C-stock, 67TS, 72TS – this bracket houses a pin arrangement which allows the bogies to rotate relative to the carbody. The housing design suffers wear on the components, and consequently generates larger impacts and loads to the surrounding structure.

Crossbeam support bracket fatigue – 92TS – issues were identified with the alignment and fit of the crossbeam support brackets which led to fatigue cracking, propagating from the bolt holes. After identification brackets were retorqued and shimmed to resolve these issues. These brackets have a fatigue life of 20 years and have been replaced through overhaul.

Crossbeam support bracket fatigue – 95TS – cracks were identified on the aluminium crossbeam support bracket, it is believed this is due to the material exceeding the number of cycles to cause fatigue cracks to initiate.

Drawgear release operation – 96TS – release jaws creep resulting in partial operation of the release jaws mechanism. This failure mode is still undergoing investigation.

AMPEP bearings – the AMPEP bearing is the primary interface with the coupler pin and have experienced wear at a higher rate than was expected. It is believed this increase in wear may be attributed to rapid acceleration when motored cars are connected/disconnected from electrified rails.

13.0 Conclusions

13.1 Escalation and incident response

The FIR notes that the decision to escalate, and the short time it took to reach senior leadership level, demonstrates due diligence on behalf of those business areas involved, particularly the Asset Operations Fleet team and the TfL Engineering team.

The decision to stand up the LU MICG immediately upon being informed of the situation ensured that plans were implemented in line with the Major Incident protocol. This provided confidence that there was strategic oversight of all impacted business areas and the right stakeholders were informed at the right time.

In Engineering, Employee Communications and Engagement (ECE) and the MICG, there was clear documentation provided on the process to follow during an incident and provide adequate assurance. In the MICG, this was the Major Incident Management Procedure which is accompanied by annual exercises, in ECE this was the LU Major/Significant Incident Procedure, and in Engineering, this was Standard G186, Manual of Good Practice, Assurance of Rolling Stock Components. The FIR determines that this structured approach enabled strategic decisions to be undertaken which prioritised safety requirements whilst also considering the impact of shutting down the Jubilee Line which in itself may have caused safety concerns in terms of congestion and wider impact on the network. The communications strategy ensured the right people were notified at the right time and with the right information.

The FIR concludes that the decision to withdraw trains in a controlled manor was appropriate to level of safety risk (considering the safety of LU customers and workforce) and made in conjunction with subject matter experts from across the business and Senior Leaders who provided an overall strategic view. As such, the management of the incident kept the risk posed to customers As Low As Reasonably Practicable. As further information became available, the assurance process followed by engineering was adapted to consider new risks.

Observation: The FIR recognises the decision to provide on-call senior engineering cover is not within TfL/LU policy but assisted in providing on-going confidence at the senior leadership level that decisions being made were based on subject matter expert knowledge in an evolving situation.

Observation: The decision to utilise independent rolling stock expertise from outside TfL represents good practice and provides further confidence that approach undertaken by LU and TfL Engineering, Asset Operations and the MICG was proportionate and adequately considered the risks. In addition to this, an independent rolling stock engineer was included on FIR panel to provide an objective engineering viewpoint.

Collaboration and knowledge sharing between organisations, particularly with regard to incidents, is an indicator of professionalism and maturity within the organisation and represents good practice.

13.2 Preliminary Engineering Conclusions

Engineering have concluded that it is likely that the failure seen on the longitudinal beams is due to deficiencies at the initial design. There have been subsequent contributory factors which have exacerbated the fracture propagation rates, particularly the addition of the seventh car.

The design and build of the Jubilee stock will be investigated as part of the final FIR, but current thinking does not necessarily point to errors made at design stage; it is possible that when the Jubilee stock was designed the technology available at the time could not have predicted this mechanism of failure. As technology has improved the design process today is much more rigorous. As a result, it is likely that if the stock was built today, the design would be more robust. This will be investigated as part of the final FIR to ensure our current design, build and assurance processes are robust enough that the deficiencies seen on the Jubilee stock would be identified at the design stage.

The engineering conclusions are detailed below:

Following the cracks found on the inner longitudinal beam on 96TS, comprehensive strain gauge testing has been carried on the underframe. The results of these were reviewed and coupled with a theoretical analysis of the performance of the train formation during traction and motoring, the mechanism under which cracks formed was established. To aid the analysis, the drawbar forces for both a 7 car and a 6 car (without a special trailer) were calculated for various scenarios.

From the strain gauge data collected in the locations where cracks have been found to form, it was possible to establish that the relationship between drawbar loads and stress generated in those locations was linear with no deviation. This is proof that the cracks are formed and *propagate as a result of the forces transferred via the coupling and are unlikely to be influenced by other factors such as track or train born vibrations.*

From the force data collected, it can be determined that in normal operation and especially at those moments where the cars with motored axles are required to provide maximum acceleration or braking, the forces being transmitted between the Non-Driver Motor car and the Special Trailer (UNDM-SPT) are almost three times greater than those witnessed by the Special Trailer to Trailer (SPT-T) car drawbar. Furthermore, there are a small number of occurrences where the loads at UNDM-SPT position more than double whilst at the SPT-T position they increase eight-fold. These events always occur when the train is exiting a station and is accelerating and can be roughly correlated with the location where one of the motor cars would lose traction as a result of conductor rail gaps due to points and crossings or traction current section changes. Conversely on braking there is no such extreme occurrences but a steady increase in loading as a result of increased passenger loading when traveling through central London during afternoon peak.

As the calculated theoretical force values correlate closely with the data collected, it is possible to evaluate the impact of the various operational characteristics and formations on the loads being transferred through the drawbars at each position. This latter theoretical work identifies that in normal operation, the introduction of the special trailer increases the highest load on the drawbar by 2.4 times. In the extreme occurrences, the effect of introducing the special trailer is almost as significant, increasing the load on all couplings on the 4-car unit by an average of 60%. However, the effects of high accelerations and regenerative braking are significant contributors. There is a direct relationship between accelerations and forces being generated, therefore a 20% increase in acceleration will have resulted in a 20% in the forces witnessed on all couplers. Furthermore, introducing 20% friction braking at trailer cars would reduce the loads during braking by approximately 30%.

Though the increases in loads through the introduction of the special car, especially when the motor car gapping is taken into account, is significant, it was deemed beneficial to estimate fatigue data for both the 7 car and 6 car formation. These calculations would not serve as accurate predictions of the actual fatigue life of the structure but provide a good indicator of the suitability of the design when implemented in both formations. In order that this could be completed, the loads recorded had to be separated into two groups, those that occur during normal operation and those that occur when travelling through areas with conductor rail gaps. Subsequently two scaling factors (one for each group) derived from the theoretical model were used to calculate the forces on a 6-car formation. The calculated fatigue life for the 6-car was multiple times lower than the expected life of the asset. There were only moderate improvements to fatigue life when all potentially negative factors were reduced or removed (e.g. gapping, improved braking, reduced acceleration).

From this latter finding it can be determined that the deficiencies in the original design and/or its implementation which lead to high stresses in the structural member, is likely to be the main mechanism of failure. The failure has been expedited through the increased loading which was introduced as part pf the 7th car project, the gapping of the motor cars during motoring and the *minimal in service friction braking on the trailer cars. Deficient conditions of the drawbar arrangement will have further expedited failure and increased crack growth rate.*

14.0 Observations

1. The design capabilities have significantly improved since the Jubilee Line was built. It is possible that other rolling stocks may also exhibit fatigue in areas that have not been identified because they were built according to the technology available at the time.

2. During the FIR panel meetings, it was identified that the implementation of CCSOs into TMRs could be more robust. Currently, actions from the CCSO are built into Maintenance Scheduled Tasks (MSTs), but these are not necessarily incorporated into the TMR and the CCSO is not referenced in the TMR. Following discussion with TfL engineering and LU Asset Operations in the panel meeting, it was identified that this process would benefit from review to ensure it is robust.

3. When reviewing the maintenance documentation, the work orders for the visual inspection were only available in hard copy. This is understandable given the time constraints, but the FIR recommends the work orders be uploaded to Maximo in retrospect in order to ensure a digital copy is available.

4. The FIR recognises the decision to provide on-call senior engineering cover is not within TfL/LU policy but assisted in providing on-going confidence at the senior leadership level that decisions being made were based on subject matter expert knowledge in an evolving situation.

5. The decision to utilise independent rolling stock expertise from outside TfL represents good practice and provides further confidence that approach undertaken by LU and TfL Engineering, Asset Operations and the MICG was proportionate and adequately considered the risks. In addition to this, an independent rolling stock engineer was included on FIR panel to provide an objective engineering viewpoint.

   Collaboration and knowledge sharing between organisations, particularly with regard to incidents, is an indicator of professionalism and maturity within the organisation and represents good practice.

15.0 Recommendations

Recommendation 1 – Establishing root cause	
Purpose	To establish the root cause from an Engineering perspective.
Action	Complete the investigation into the Engineering and technical root cause.
Action Owner	Nigel Tate, Head of Rolling Stock LU Engineering
Action Target Date	31st May 2020
Validation	Final FIR presented to DRACCT
Validator	Graham Neil, Head of Profession Vehicles
Validation Target Date	12th July 2020

Recommendation 2 – Implementation of controls	
Purpose	To ensure monitoring of the risk of longitudinal beam fractures continues for both the Northern and Jubilee Line stock.
Action	Update the TMR to reflect the recommended monitoring and maintenance as determined by TfL engineering via the Jubilee Line CCSO and the Northern Line PST. This can be achieved by building Maintenance Scheduled Tasks (MSTs) into the TMR.
Action Owner	Lee Milledge, Fleet Manager Jubilee Line Richard Thomson, Head of Fleet, Northern line
Action Target Date	28th February 2020
Validation	Review maintenance records to provide evidence of inspection of the longitudinal beams as per the TMR.
Validator	Graham Neil, Head of Profession Vehicles
Validation Target Date	30th June 2020

Recommendation 3 – Future assurance of safe operation	
Purpose	To ensure monitoring of the risk of longitudinal beam fractures continues for the life of both the Northern and Jubilee Line stock.
Action	TfL Engineering to determine frequency of inspection required for the life of the Jubilee and Northern Line fleets once the technical root cause has been investigated.
Action Owner	Nigel Tate, Head of LU Rolling Stock Engineering
Action Target Date	TBC final FIR – the inspection regime is currently determined by the CCSO. Once repairs and investigation have been completed this will enable a risk based approach to be employed to determine monitoring regimes.
Validation	Review maintenance documentation - inspection regime will be proportionate to the level of risk with new fractures being identified before they reach Category 1 stage.
Validator	Graham Neil, Head of Profession Vehicles
Validation Target Date	12 weeks post action date

Recommendation 4 – Relating to Observation 1	
Purpose	To reduce the risk of issues on other fleets not being picked up in routine inspections.
Action	A) Once the root cause has been established, TfL Engineering to identify at risk lines which may have design issues due to being designed and built in a time when the technology available was less sophisticated than today. B) Design maintenance/monitoring regimes for at risk lines. Draw on industry knowledge outside LU to determine a way to identify issues that may not form part of routine inspections e.g. zonal checks from the aviation industry.
Action Owner	Nigel Tate, Head of LU Rolling Stock Engineering

Action Target Date	Action target date to be set in final FIR once root cause has been established.
Validation	Review monitoring plans for lines which may be considered as being at risk.
Validator	Graham Neil, Head of Profession Vehicles
Validation Target Date	6 weeks post implementation of action 4B

Recommendation 5 – Relating to Observation 2	
Purpose	To ensure the actions identified from the CCSO which are subsequently made into MSTs follow a robust process across LU Fleet.
Action	A) Review process for the ongoing interaction between engineering and maintenance in terms of the CCSO, MSTs and TMR. B) Update and implement process
Action Owner	Nigel Tate, Head of LU Rolling Stock Engineering
Action Target Date	A) 31st January 2020 B) TBC following completion of action 5A
Validation	Process should ensure that if a Fleet Manager with no prior knowledge of the CCSO reviewed the TMR, it would be clear why the inspection regime was in place.
Validator	Graham Neil, Head of Profession Vehicles
Validation Target Date	8 weeks post implementation of action 5B

Recommendation 6 – Relating to Observation 3	
Purpose	To ensure fleet maintenance record keeping is robust.
Action	Raise Work Orders relating to this incident and repairs retrospectively on Maximo for the once round check to ensure a digital copy is available.

Action Owner	Lee Milledge, Jubilee Line Fleet Manager
Action Target Date	01st April 2020
Validation	To provide assurance that an accurate digital log is kept for future auditing.
Validator	Paul Downham, Acting Head of Fleet
Validation Target Date	30th April 2020

Recommendation 7 – Improving data capture during incidents	
Purpose	To ensure that decisions are correctly recorded as soon as possible to reflect the rationale for that course of action. This will facilitate the ongoing effective management of the incident and enable the correct level of scrutiny and review.
Action	Review the approach for logging decision making and introduce where required improvements to incident management
Action Owner	Tim Scott, Resilience Strategy Manager
Action Target Date	31st March 2020
Validation	Review implementation of any changes post incident to ensure effectiveness.
Validator	Richard Jones, Head of Network Delivery
Validation Target Date	31st May 2020

Recommendation 8 – Relating to a Work Instruction error identified during the 2012 overhaul	
Purpose	To reduce the risk of human error when issuing and modifying Work Instructions across LU Fleet.
Action	Review the process for issuing and modifying Work Instructions to ensure human error is mitigated against.
Action Owner	Paul Downham, Acting Head of Fleet

Action Target Date	31st March 2020
Validation	Assurance to ensure the risk of human error is captured in the sign off process.
Validator	Graham Neil, Head of Profession Vehicles
Validation Target Date	30th April 2020

Recommendation 9 – Reviewing the ABRA and QRA	
Purpose	To ensure the relevant ABRA and QRA are reviewed and updated to reflect the risk of fractures and potential subsequent derailment across all LU fleets.
Action	Safety, Health and Environment Specialist Team to agree programme of ABRA/QRA review with TfL Engineering for all tube stocks.
Action Owner	Nigel Tate, Head of LU Rolling Stock Engineering Tekpenor Anim, Senior HSE Manager
Action Target Date	28th February 2020
Validation	Review programme commenced.
Validator	Graham Neil, Head of Profession Vehicles
Validation Target Date	30th June 2020

16.0 Appendices

16.1 Formal Investigation Panel Members

Name	Title	Organisation
Claire Porter	Head of Transport Systems	TfL
Kate Hagan	Lead Investigator	LU
Kevin Crofts	Independent rolling stock specialist	SNC Lavalin
Claire Maclean	New Stock Engineer	TfL
Steve Whysall	LU Rolling Stock Mechanical Engineering Manager	TfL
Lee Milledge	Jubilee Line Fleet Manager	LU
Marian Kelly	Head of HSE LU	TfL
Steve Cordell	Health, Safety & Environment Manager	TfL
Graham Stanbridge	Health and Safety Representative RMT (Trains)	LU
Martin Bell	Health and Safety Representative ASLEF (Trains)	LU
Christopher Green	Health and Safety Representative RMT (Fleet)	LU
Michael Peralta	Health and Safety Representative UNITE (Fleet)	LU

16.2 Persons Interviewed

Title	Organisation
Train Maintainer	LU

16.3 Consultation

Title	Organisation
Safety, Health & Environment Manager (Risk Assessments)	TfL
Network Security Manager	TfL

Jubilee Line Fleet Maintenance and Assurance Manager	TfL
Head of Integrated Assurance	TfL
Communications Manager (Press Office)	TfL
Senior Communications Manager (ECE)	TfL
Jubilee Line Service Manager	LU

17.0 Document Appendices

17.1 Case for Continued Safe Operation 'longitudinal crack' Number 394, Issue 1

F0107 A5

Fleet - Case for Continued Safe Operation (CCSO)

UNDERGROUND

Complete all grey fields on the form. Attach photographs and updates as required to the appropriate sheets.

Title	Longitude Crack		
Vehicle Type	96TS	**CCSO Number**	394
		Issue	1
		Status	**Active**

Prepared By	William Marshall
	(Fleet Competent Person [redacted]

Reviewed By	Steve Whysall [redacted]
	(Principals Engineer)

Reviewed By	
	(Additional Principals Engineer if required)

Reviewed By	Lee Milledge
	(Fleet Manager) [redacted]

Accepted By	Helen Carrington [redacted]
	Head of Rolling Stock

Issue Number	Date	Comments
1	18.10.2019	**First Issue**

Distribute: the names above, Materials Management, ESM, FEM, FCP, FM, LMAE, HoRS, Senior Electrical and/or Senior Mechanical Engineer, RS Engineering Manager, Maintenance Planning Manager

Used in conjunction with PR0155
Valid on day of printing: 18/10/2019

Formal investigation report: interim report

F0107 A3

Fleet - Case for Continued Safe Operation (CCSO)

Title	Longitudinal Crack	**Status**	Active
		CCSO Number	394
		Issue	1

Incident Information		
Date	17/10/19	
Time	14:00	
Location	Stratford Market Depot	
Vehicle No.	96609	
Vehicle Type	96TS	
Affects other fleets?	Yes	95TS & 92TS
Vehicle Environment	Maintenance	

Defect Description
During Exam large cracks were found on the longitudes on both sides of D end on car 96609.

Immediate Cause
The stresses caused by buff and draw loads experienced by the longitudes have caused fatigue cracks to form.

Actions Taken At The Time
The fleet is being inspected against 'Longitude Inspection Record', as per email William Marshall 17/10/2019 19:47. This has four categories of crack; any unit with a category 1 crack is stopped. Any unit not inspected by Start of Traffic on 18.10.2019 is not being offered for passenger service.

Operating Restrictions (if any state how Operations informed)
None

Lee Milledge

Principles Engineer's Statement
The cracks initiate in the region of the last fixing on the inner longitude or at the inner radii. The coupler bracket is stiff in comparison to the longitude and has a sharp stiffness transition resulting in a high stress at these locations. The 7th car location between the UNDM and another trailer car results in the location with the highest buff and draw loading. The most significant cracks have been located at this location, however smaller cracks have been identified at other car locations.
The initial visual once round is being carried out to identify assemblies that are at risk of failure in the short term, to ensure that no high risk vehicles remain in service. All trains have been checked before entering service. It will be necessary to complete NDT testing of all cracked longitudes and then all remaining longitudes to ensure the full extent of all cracks is known and any of concern removed from service.
A further review of the run criteria will be made on completion of the NDT assessment. A short term repair procedure will be trialled and proven by FEA and in-service strain gauging to allow time for a long term repair to be developed.
With these mitigations in place the risk of catastrophic failure of the coupler arrangement is reduced to a tolerable level to allow continued safe operation of the fleet.

Asset Risk Register Information (Principles Engineer to complete)

Top Event	Derailment	
Base Event	Miscellaneous large object falls from Train	
Zone	16	Underframe
Defective Component	Longitudinal	

Failure Mode
Fatigue cracks have initiated in the longitude

Failure Effect
Continuation of the cracks would lead to detachment of the coupler assembly.

First Issue

Safety Risk (Unmitigated)		
Consequence	Frequency	Risk Level
4	4	16

Safety Risk (Mitigated)		
Consequence	Frequency	Risk Level
4	2	[illegible]

ACTIONS

Action Number	Action	Action Holder	Completion Date	Status	Safety Mitigation	Closure Evidence
1	Carry out a visual once round on the fleet in accordance with 'Longitude Inspection Record'. Any unit not inspected by SoT on 18.10.2019 shall not be offered for passenger service.	Fleet - Fleet Manager	23.10.2019	Open	Yes	Email from FSM with summary result sheet
2	Carry out NDT of all CAT 2, 3 and 4 cracks.	Fleet - Fleet Manager	25.10.2019	Open	Yes	NDT records
3	Carry out NDT of all positions on the fleet not covered by action 2	Fleet - Fleet Manager	25.11.2019	Open	Yes	NDT records
4	Produce a report to describe the failure mode.	LU OPS - Mechanical Engineering	15.10.2019	Open	No	Signed report
5	Define an NDT regime to be incorporated into the maintenance regime based on refined definitions of crack category	LU OPS - Mechanical Engineering	17.01.2020	Open	Yes	Issued CRS
6	95TS Fleet to carry out a visual once round against 'Underframe Crack Check Alarm Diagram' on 25% of the fleet	Fleet - Fleet Manager	18.10.2019	Closed	Yes	List of closed Service Orders
7	Review 92TS design and determine next steps.	LU OPS - Mechanical Engineering	24.01.2020	Open	No	Email from Principles Engineer

Used in conjunction with PR0155
Valid on day of printing: 18/10/2019

17.2 Independent report from Xanta Rail

This note is provided at your request to give an independent view of how the work on containment and rectification of the fracture problem is being managed. It is confined to the scope agreed for engagement with this work, which is to limited to review of:

- The Case for Continued Safe Operation in terms of the degree to which it demonstrates that safety risk is As Low As Reasonably Practicable (ALARP) through its continued use and the degree to which its provisions help to support effective service delivery.
- The emerging response to repair (interim and permanent) in terms of the risks to successful resolution based upon diagnosis of the causes of failure and how they are addressed by the proposed repairs.

You will appreciate that this is a view based on less than 24 hours engagement, but as it is based on the review of relevant documents and discussion with relevant people in TfL, it is soundly based. It will be updated as required subsequently.

TfL has a standard which deals with the current circumstances – G186, Manual of Good Practice, Assurance of Fractured Rolling Stock Components. It covers all that is required and so commentary is made on current circumstances with respect to that standard.

The principal requirement is to contain the problem and establish criteria for continued safe use of the affected vehicles. This has been done as envisaged in G186 and a Case for Continued Safe Operation (CCSO) produced. The CCSO depends upon categorisation of failures according to their severity. The most severe are removed from service until a repair scheme is in place. Vehicles with damage in the less severe categories are allowed to be operated subject to a scaled inspection regime; the more severe the damage the more frequent the inspection. This protects against crack growth reaching the most severe levels originally found.

Even the most severe damage has not resulted in catastrophic failure, and its removal from service with only less severe damage being present, subject to a scaled inspection regime, underpin the CCSO which is predicated on the absence of unacceptable risk of catastrophic failure. This is a reasonable and supportable conclusion to have reached. It is possible to go further and to state this represents a state in which safety risk is ALARP because;

- The amount of effort being applied to contain the problem is consistent with 'reasonable' levels of expenditure defined by DfT Value of Prevented Fatality criteria; there would be no way of spending the sums implied by the VPF criteria to beneficial effect beyond that already being spent; and
- What is being done is self-evidently 'reasonably practicable' and relevant to the problem through its compliance with G186, which is an established and proven response to such problems.

Because the approach has categorised failure severities with appropriate response criteria, it also provides an effective response to the need to provide continued service operations; only vehicles that are safe to operate are operated providing the level of service that can be provided. The only alternative is no service.

At this point design of a repair scheme is in its earliest stages and an interim repair pending full resolution is likely. Before either can begin further insight is required into the root cause of failure. This is a basic requirement of G186; a permanent repair cannot be known to be effective unless it is known why the failure happened. This understanding is emerging but is not yet complete. The interim repairs, which may proceed without a full understanding being available, need only be adequate for the time-limited use to which they will be subjected. Their use may include ongoing inspection regimes.

What can be said is that:

- The original design does not represent good practice; there are rapid changes in stiffness over short distances in the locality of the fractures exacerbated by the use of steel and aluminium as part of the same joint. The 1995 (Northern Line stock) has a similar but better design which uses aluminium only; but
- The intended operation of the design needs to be better understood. Failures exhibit what look like large bending moments applied locally to the joint close to the fractures. This clearly arises from drawbar forces but should have been reacted by fastenings at the other end of the assembly (towards the car centre). This arrangement should be able to deal with at least some of the apparent shortcomings of rapid changes in stiffness, but did not. Investigation is underway to understand why not. Focus will include the effectiveness of the two bolts on each side attaching the tiebar assemblies to the underframe towards the centre of the carbody; and
- It is clear that the bolted joints have been overtightened by 50% as described in documentation available from 2012. This may have caused local damage in the aluminium flanges which have fractured by causing creep deformation allowing the bolted joints to loosen over time after initial tightening. This was not properly investigated at the time and it is not clear that the recommended inspection of the flanges was undertaken.

These matters will be expanded until an adequate understanding is available.

Overall, a competent response is in place and should be allowed to continue.

Many thanks,

Director - Xanta Limited

17.3 Letters of Assurance

Transport for London

18 October 2019

Transport for London
Engineering Directorate

11th Floor
Palestra House
197 Blackfriars Road
London SE1 8NJ
Phone [redacted]
Email: [redacted]@tube.tfl.gov.uk
www.tfl.gov.uk

Jubilee line safety issues - Engineering assurance

Dear colleague,

Safety inspections, carried out as part of the normal fleet maintenance, have uncovered an issue on some of the Jubilee Line trains. As a precaution, and because safety is our top priority, we have removed Jubilee Line trains from service for further detailed inspections to ensure your safety and that of our customers.

After assessing the situation, my Rolling Stock Engineers have set clear criteria, linked to the issue discovered, which the train has to meet in order to be deemed fit for service. No train will enter service if it has any faults which might compromise your safety or that of our customers.

The Fleet depot maintenance staff are working around the clock to carry out inspections. Trains that are passed fit will be ready for return to service and work will begin immediately to progress the repair of those which fail the assessment criteria. We will do everything we can to safely operate a service on the Jubilee line, but this will depend on the outcome of overnight inspection assessments and other fleet works.

No train will enter service if it has failed the assessments as we seek to ensure that there is no compromise to your safety or that of our customers.

No other lines are affected. The Northern line runs similar trains to the Jubilee line, but we have checked and confirmed that there is no evidence of a similar problem.

[redacted]

George Clark

TfL Director of Engineering

MAYOR OF LONDON

Transport for London

London Underground

UNDERGROUND

17 October 2019

London Underground
Health, Safety & Environment

7th Floor
Palestra House
197 Blackfriars Road
London SE1 8NJ

Phone [redacted]
Email [redacted]@tube.tfl.gov.uk
www.tfl.gov.uk/tube

Dear colleague

Jubilee line safety issues

Our usual safety inspections have uncovered an issue on some of our Jubilee line trains. As a precaution, we have removed these trains from service for further detailed inspections.

Our priority remains the safety of our staff and customers. I have been assured by TfL's Director of Engineering that no trains will enter service if it has any faults which might compromise the safe operation of the Underground. The inspections being carried out by the TfL Engineering team will ensure that we will only operate trains where it is safe to do so.

The remainder of the network is unaffected, although the reduction in service will result in other lines and stations being far busier than usual. We have robust and well rehearsed emergency plans to ensure that we can manage the safe operation of the network.

I have spoken to Keith Atkinson at the Office of Rail and Road (ORR) to inform him of the issue. He remains satisfied that we have robust plans in place to manage our service safely.

Yours sincerely

[redacted]

Marian Kelly
Head of HSE London Underground

17.4 Reporting of Injuries, Diseases and Dangerous Occurrences Regulations Report

RIDDOR: Dangerous Occurrences **Total this week ~ 2** **24/10/2019**

Incident Ref | Date & Time	Line | Department	Location | Incident Summary Notes	RIDDOR: Category
039983 15/10/2019 21:33:00	Customer Service - District Line Stations Operations - Fulham Broadway Area	East Putney Running Line (open) At 21:33 Hours Westbound Train 052 was delayed arriving at East Putney - Report Of Bridge Strike W052 (21385) was delayed arriving to the platform. This was due to the Network Rail Shift Manger advising the District SM of a late notice bridge strike on bridge D231. The bridge strike allegedly occurred at around 20:30. In line with NwR procedures, as 10+ trains passed over the bridge, without any issues, W052 was allowed into the platform. A job was raised via the FRC 9801648. The MoM and DRM attended the site and there was no evidence of any damage to the structure or brickwork. Delay 6 minutes Safety and Security Alleged bridge strike MOM and DRM attended with no issues found and area declared safe	DO73e - Bridge strike by a road vehicle (e.g. lorry or bus) if likely to cause Accident or Injury
106241 18/10/2019 05:00:00	Fleet - Jubilee Fleet - Jubilee Management	Stratford Market Depot Passenger Train (underneath) Cracking was identified on one of the couplers which connects the train carriages to one another on the Jubilee Line. Once this fault was identified, further trains were checked which led to a decision to make detailed checks of the entire fleet and then remove a number of trains from service. The cracks all appear in the same location on these trains, as it is the point of highest stress. No other lines are affected. The Northern line run similar trains to the Jubilee line, and as a precaution, the Northern line fleet have been checked which confirmed the same issue does not exist. The cracks form in a uniform and consistent pattern. Visual inspections, ultrasonic and other industry standard tests have been used to determine the extent of the cracks on individual trains. These tests have allowed the classification of faults from category 1 (remove from service) to categories 2-4 (available for service, but subject to an enhanced testing regime so that we can closely monitor the cracking). We have taken a conservative approach to this categorisation and the re-inspection regime, again putting the safety of our customers and our people first. Whilst preparing to make repairs, we have ascertained an additional measure to further reduce the stress impact on category 2 trains. As a result, we've temporarily taken the category 2 trains out of service to enable our engineers to install this precautionary measure. LU engineers regularly use inspection regimes with specified pass and fail criteria, and with periodic re-inspection in place to ensure our assets remain safe. This is standard engineering process. In this case, LU engineers have produced an enhanced inspection regime that errs on the side of caution, ensuring a train will be checked before there is any risk of failure. A formal investigation will be undertaken to identify the reason for this fault and to understand how to prevent this happening again. The Office of Rail and Road (ORR) have been informed of the issue and the action taken.	DO63 - Train - Failure of Axle or Wheel or other part likely to cause Accident/Injury

17.5 Engineering investigation action tracker

FIR	Question	Category	Difficulty	Report	Report Delivery Date	Evidence
32a	Has there been any modifications near to the cracks that could have induced them/	Historical Information	1. Short	Changes impacting buff and draw loading	24/01/2020	Past CRS's; modifications to drawgear/coupling
32b	What changes have occurred to cause the cracks to form?	Line Testing	2. Medium	Test Report - Analysis	24/01/2020	Determine Loadings across units and at what vehicle activity causes peak loads
33	Where is the documentation from 2012 (in **Xanta report**)? Why was it not investigated when it was picked up?	Bolt Failure data	2. Medium	Bolt Failure Report	Complete	Over Torqueing of Bolts, calculations and CCSO Actions with poor requirements
34	Were there any unusual circumstances such as vibration, juddering trains?	Line Testing	2. Medium	Test Report - Analysis	24/01/2020	Determine Loadings across units and at what vehicle activity causes peak loads
35	Is it because of the rough ride (track)?	Line Testing	2. Medium	Test Report - Analysis	24/01/2020	Determine Loadings across units and at what vehicle activity causes peak loads
36	Were the welds NDT post construction?	Manufacture	2. Medium	Train Manufacture Report	Complete	Alstom design specification / Documentation and measured train data
37	Why were the failures not distributed across the fleet?	Line testing	2. Medium	Fatigue Life Report	Complete	Demonstrate the loading variance and associated fatigue life across units
38	Why did 3 of the first 4 trains have fractures, but only 8/9 of the entire stock? The first inspections had a much higher failure rate. (added from question 37)	General Questions	1. Short	General Report 1	Complete	Probability of inspection
39	Why has it taken so long to crack?	Line testing	2. Medium	Fatigue Life Report	Complete	Demonstrate fatigue life across units
40	How fast will the cracks propagate?	Crack Data	2. Medium	Crack Data Analysis Report	Complete	Determine Crack Growth rates from crack data across different categories
41	How long did the fracture exist before it was picked up?	Line Testing	2. Medium	Fatigue Life Report	Complete	Demonstrate fatigue life across units
42	Have tests proved the reason for the crack theory?	Line Testing	2. Medium	Fatigue Life Report	Complete	Demonstrate fatigue life across units

43	Is ATO a factor?	Line testing	2. Medium	Test Report - Analysis	24/01/2020	Determine Loadings across units and at what vehicle activity causes peak loads
44	Does the cyclic nature of ATO (especially in the early days) impact on this?	Historical Information	2. Medium	Changes impacting buff and draw loading	24/01/2020	Identify historical evidence of previous issues that occurred in early introduction of the ATO system
45	Was there any testing for stresses/strain in ATO – at speed, full loading, poor track?	Line testing	2. Medium	Test Report - Analysis	24/01/2020	Determine Loadings across units and at what vehicle activity causes peak loads
46	Why was the issue not identified at design?	Train design	1. Short	Original design report	Complete	Standard requirements - Joe email assessment of work done plus any additional findings
47	Is the design proved (when compared to other fleets/trains)/How does the design compare to other similar train/coupling types?	Train design	2. Medium	Original design report	24/01/2020	Design comparison with other stocks
48	Are the designs in this area the same on all car types? If not, why the difference?	Train design	1. Short	Original design report	Complete	Design the same across cars
49	Who designed the beam? Who approved/accepted it in LU? What standard applied?	Train design	1. Short	Original design report	Complete	Standard requirements - Joe email assessment of work done plus any additional findings
50	What properties of the metal contribute?	Line testing	1. Short	Fatigue Life Report	Complete	Demonstrate fatigue life across units and show the fatigue life / class of different features.
51	What does the original FEA for longitude show?	Train design	2. Medium	Original design report	Complete	proof load case in FEA, static - was a fatigue assessment completed as part of line testing
52	Is the extra car a strain on drawgear/coupling plate compared to original six car train when accelerating/braking?	Line testing	2. Medium	Test Report - Analysis	24/01/2020	Determine Loadings across units and at what vehicle activity causes peak loads
53	What is the effect of galvanic corrosion and could this be a factor?	General Questions	1. Short	General Report 1	Complete	Evidence of corrosion or adverse chemicals environment
54	Could temperature extremes in weather be a factor?	General Questions	1. Short	General Report 1	Complete	Evidence of adverse thermal environment
55	Why was it not reacted by fastenings at the other end? (Xanta report)	Train design	1. Short	Original design report	Complete	Alstom design specification; assurance documents

56	Why does the original design not represent good practice? (Xanta report)	Train design	1. Short	Original design report	Complete	rapid changes in stiffness over short distances in the locality of the fractures exacerbated by the use of steel and aluminium
57	Is there a risk of drawgear detaching from the train partially/fully?	Assurance	1. Short		24/01/2020	CCSO failure - mitigations in place to reduce the risk
58	What was the design assurance?	Assurance	2. Medium		Complete	
59	Impact of failed bearings on loadings and stresses?	Ampep Data	1. Short	Ampep Bearing Report	Complete	AMPEP bearing data; analysis
60	Does the way this train brakes have an impact?	Line Testing	2. Medium	Test Report - Analysis	24/01/2020	Determine Loadings across units and at what vehicle activity causes peak loads
61	Why more cracks on some units?	Line Testing	1. Short	Fatigue Life Report	Complete	Demonstrate the loading variance and associated fatigue life across units
62	Why did the beam fracture?	Line Testing	1. Short	Fatigue Life Report	Complete	Demonstrate the loading variance and associated fatigue life across units
63	Is it because of the concrete block? I.e. does the load affect this design?	Line Testing	2. Medium	Original design report	Complete	Ballast on special trailers % of additional mass compared to total car mass plus crush
64	Particular cars with fractures - Is it because they were built with different metals?	Train design	2. Medium	Original design report	Complete	This is root cause but it ties in Q. 61
65	Has passenger/mileage increase been a factor/did the increase in train km have any impact on fracture? (How many km does the Jubilee run now compared to 1997?)/Was the 96RS designed for current levels of use?	Historical Information	1. Short	Impact of timetable increases	Complete	Kilometerage data - timetable comparison; Alstom design specification
66	Did the materials used all come from the same supplier?	Train design	2. Medium	Original design report	Complete	Material specs from build and N17
67	Have the drawgear modifications been reviewed as recommended in initial report?	Historical Information	2. Medium	Changes impacting buff and draw loading	24/01/2020	Identify historical evidence of previous issues that occurred before mod - AOS-E-RS-Int-I040-TR_16-No-913-A1 section 3.3
68	Were the 7th car and existing stock built to the same spec?	Train design	2. Medium	Original design report	Complete	Alstom design specification; assurance documents

69	Do we have any evidence on the history of drawgear failures?	Historical Information	2. Medium	Changes impacting buff and draw loading	24/01/2020	Identify historical evidence of previous issues
70	Why wasn't the service stopped when structural faults were found?	Assurance	1. Short		Complete	
71	At what point do the cracks mean it is unsafe to run?/ what is safe to run in service?	Line testing	2. Medium	Fatigue Life Report	Complete	Demonstrate fatigue life across units
72	Was it safe to run the Jubilee line on 17th October at 1800, 2100, 2300? I.e. What was the review and reassessment process?	Assurance	1. Short		Complete	
73	How was the decision made on which trains should be pulled from service?	Line Testing	2. Medium	Fatigue Life Report	Complete	CAT 1 - CAT 4 category criteria
74	What could have been the potential consequences e.g. derailment risk?	Assurance	1. Short		Complete	
75	Who provides the assurance it is safe to run trains?	Assurance	1. Short		Complete	
76	Were the categories correct?	Line testing	2. Medium	Fatigue Life Report	Complete	Demonstrate fatigue life to for propagation rate to justify categories given
77	Is the Northern Line safe to run? What is the status of northern line fractures? Has NDT been carried out in this area?	Assurance	1. Short		Complete	
78	Do we need to check other fleets?/Does this affect other LU rolling stock?	Historical Information	2. Medium	Review of assemblies on other Fleets	24/01/2020	Provide details of other designs and issues that have occurred and what solutions have been put in place
79	Which process are we following?	Assurance	1. Short		Complete	
80	Has this happened before on LU rolling stock or other rolling stock?	Historical Information	1. Short	Review of assemblies on other Fleets	24/01/2020	Provide details of other designs and issues that have occurred and what solutions have been put in place
81	Possible similar failure on circle line – what did we learn? Who did we pass on information to?	Historical Information	1. Short	Review of assemblies on other Fleets	24/01/2020	Provide details of other designs and issues that have occurred and what solutions have been put in place

82	How do we know the competence of the people dealing with the incident? W0165 delegation of technical authority	Assurance	1. Short		Complete	
83	Is wheel turning the carriage wheels a factor?	General Questions	1. Short	General Report 1	Complete	Effect of small and big wheels
84	What is the monitoring and assurance for Ampep bearing failures?	Ampep Data	1. Short	Ampep Bearing Report	Complete	AMPEP bearing data; analysis
85	What was the assurance process?	Assurance			Complete	
86	What is the assurance process across LU fleet – how can we be sure it is safe to run trains?	Assurance			Complete	
87	What is the summary of decision making over the first week?	Assurance			Complete	
88	What is the current understanding of root cause from a mechanical perspective?	Assurance			Complete	
E1	How the decision was reached to change category 2 trains from run for 3 days to stop.	Bolt Failure data	1. Short	Bolt Failure Report	Complete	CAT 1 - CAT 4 category criteria; changed about 20th October
E2	What are the details of the bolt failures	Bolt Failure data	2. Medium	Bolt Failure Report	Complete	Details of the bolt failure
E3	What assessments were made for this location for the introduction of the 7th Car	Historical Information	2. Medium	Changes impacting buff and draw loading	24/01/2020	Determine what analysis was undertaken
E4	What assessments were made for this location for the introduction of ATO	Historical Information	2. Medium	Changes impacting buff and draw loading	24/01/2020	
E5	What was the impact of bolt over torque of fixings	Bolt over torque	1. Short	Bolt Failure Report	Complete	Review of the CCSO actions and impact of decisions made
E6	Why does the vehicle latch?	Latching	2. Medium	Latching Report	24/01/2020	
E7	What effect does latching have on the fatigue life of the longitude?	Latching	2. Medium	Latching Report	24/01/2020	
E8	What is the effect of the as-built flatness tolerance exceeding 0.5mm specified?	Manufacture	1. Short	Train Manufacture Report	Complete	

17.6 Example of the daily flash report summary

S - Longitudinal fatigue crack - Cumulative flash report

03/12/19

Performance Indicator	Today 14/11/2019	Δ 24h	13/11/2019	12/11/2019	11/11/2019	10/11/2019	09/11/2019	08/11/2019	07/11/2019	06/11/2019	05/11/2019	04/11/2019	03/11/2019	02/11/2019	01/11/2019	31/10/2019	30/10/2019	29/10/2019	28/10/2019	27/10/2019	26/10/2019	25/10/2019	24/10/2019	23/10/2019	Target	RAG	Percentage of
Repair Progress																											
Category B Repair (Cat 1)	0	→	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Category A Repair (Cat 2)	2	→	2	2	2	2	2	2	2	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	2		
Service Provision																											
Number of units available without category 1 or 2 defects	115	→	115	115	115	N/A	N/A	117	117	114	114	115	115	115	115	115	104	104	115	115	115	115	117	117	126	N/A	91.3%
Trains offered for service	49	↓ -3	52	48	49	40	37	49	50	51	47	47	43	36	50	48	49	50	49	39	40	50	48	48	58		84.5%
Defect Status																											
Category 1 units	7	→	7	7	7	-	-	6	6	8	8	9	9	9	9	9	9	9	8	9	9	9	8	8	0	N/A	5.6%
Category 2 units	4	→	4	4	4	-	-	3	3	4	4	2	2	2	2	2	2	2	3	2	2	2	1	1	0	N/A	3.2%
Category 3 units	7	→	7	7	7	-	-	6	6	6	6	6	5	5	5	5	4	3	3	1	1	1	0	0	0	N/A	5.6%
Category 4 units	20	→	20	20	22	-	-	20	20	19	18	18	16	16	16	16	15	14	14	14	14	13	10	10	0	N/A	15.9%
NDT status																											
NDT actual (cumulative)	109	→	109	107	105	104	104	102	98	97	94	89	85	85	81	75	75	68	62	56	50	40	-	-	153		86.5%
Clean Units Post NDT (Fracture Free)	79	→	79	77	75	-	-	73	69	67	63	60	57	57	57	54	48	45	-	-	-	-	-	-	126		62.7%
Units remaining to NDT	17	→	17	19	21	22	22	24	28	29	32	37	41	41	45	51	51	58	64	70	76	86	-	-	-27		13.5%

17.7 Example of the daily flash report

96TS longitudinal fatigue crack – Daily flash report

22nd October 2019

- Confirmation was received that it is safe to run the Railway from Steve Whysall/Nigel Tate
- The decision was taken to stop category two trains, due to…
- 51 of the 63 trains are running (81%)
- There are:
  - 9 category 1 trains
  - 2 category 2 trains
  - 0 category 3 trains
  - 10 category 4 trains
- NDT testing was carried out on 5 trains.
- There are no trains at risk of being taken out of service in the next 7 days.

96TS - Longitudinal fatigue crack - daily flash report — **22 October 2019**

London Underground Engineering – Period 7 2019/20

Metric

Performance Indicator	Actual	Target	RAG
Number of trains available for service	51	63	
Category 1 trains	9	0	
Category 2 trains	2	0	
Category 3 trains	0	0	
Category 4 trains	10	0	
NDT actual (cumulative) vs. planned	5	10	
Trains at risk in next 7 days	0	0	

Note: 1 train is stopped for mid-life refurbishment

CAT Run Criteria		Definition of the category
CAT 1	STOP	Worst cracked web has a crack or cracks which extend to the edge or to within 50mm of the edge more than once
CAT 2	Run for 3 days and re-inspect	Worst cracked web has two cracks, one linear and one radial, which intersect. Only one crack extends to a single edge or within 50mm of an edge
CAT 3	Run for 7 days and re-inspect	Worst cracked web has two cracks, one linear and one radial that do not intersect. Cracks on different faces do not interconnect
CAT 4	Run for 28 days and re-inspect	Worst web has one crack, one linear or radial. Cracks on different faces do not intersect

17.8 Control tower log from SMD

18/10 2019 1:51 AM FAX 02079180290 SMD TOWER 0001/0001

MAYOR OF LONDON

Transport for London UNDERGROUND

Title:	J2 Declaration of Trains Handed over to Fleet Stratford Market Depot

*If train handed over on this form is an un-braked move please put Yes in the box for relevant train Production manager to follow process complex defective train handover process JNP-JLF-PRC-00017 using the hand over form JNP --JLF-FOR-00008

Road	Train	Arrival Time	Leading Cars	Defects reported to DMTM	*Yes	Wash Side/Full
41	352	21-40	54-53	FX		✓
21	364	21-51	12-41			✓
22	353	21-57	108-27	FX		✓
20	365	22-06	82-81			
~~28~~	~~337~~		~~28-77~~			
38	301	22-57	~~28-77~~	56-43		
39	337	23-03	28-77	FX		
18	333	23-10	30-75			
17	312	23-29	20-99			
15	332	23-39	118-113			
16	336	23-45	116-101	FX		✓
26	346	23-30	66-21			
24	334		58-85			✓
33	310		104-17			
23	307		114-29	txd 0017		
22	342		76-1			
21	371		110-109	txd 0040		[illegible]
38	315		60-5			
19	345		14-69			✓
7	326		24-63			
6	327		84-89	txd 0054		
5	321		162-49			
40	351		36-117			
42	306		124-123	txd 0114		
39	355		68-47	" 0128		
41	323	(0152)	120-119			

I certify that the above trains have completed passenger service/train movements and have been officially handed over to Fleet Stratford Market Depot.

Name: Andy .... Employee No: ....

Signature: [redacted] .... Date & Time: 17.10.19...........

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LU Engineering – AOS Rolling Stock

Palestra, 197 Blackfriars Road, London.

TITLE: 96TS Carbody Longitude Cracks Investigation Summary Report

Ref: AOS-E-RS-Int-J067-TR_16-No-1007-A1

Prepared By: Steve Whysall **Date**

[redacted] 07/07/2020

Reviewed By: Loucas Papaloucas **Date**

[redacted] 07/07/2020

Approved By: Nigel Tate **Date**

[redacted] 07/07/2020

Date Issued and Version:

Version	**Date**	**Comments**
R1	05/06/2020	Draft for internal review
R2	10/06/2020	Draft Issue for FIR and Independent review
A1	01/07/2020	Issued

1. Executive Summary

The investigation into the Jubilee Line carbody longitude cracks completed by LU Rolling Stock Engineering with the support of LU Technical Services, JNP Fleet and JNP Fleet Engineering identified the following key causal factors which resulted in a low fatigue life on the carbody longitude causing cracks to occur.

The loadcases used to validate the L14 vehicles design were taken directly from the mandatory minimum requirements within the specification. There is a requirement for the contractor to identify and assess other areas of concern, but critically a fatigue case for the intercar coupler forces was not considered.

Within the later Alstom submissions to support the approval of the additional L17 cars and introduction of ATO (L19) there was an assumption that the coupler system was designed for a 7-car formation. This is correct with respect to crashworthiness but at no point was a fatigue assessment of the coupler in-service loads considered in either the six or seven car formations.

Both the L17 and L19 projects' acceptance was based upon demonstrating any variances to the original L14 approval were acceptable. As a fatigue assessment of the in-service intermediate end forces was not an original requirement there was no variance and no fatigue assessments were made even though both projects' changes had a negative impact on the coupler forces, particularly the introduction of the special trailer car.

When a special trailer car was added to a unit (which reduced it to 50% motored) it increased the forces at all intermediate end couplers within a train, most significantly between the UNDM to special trailer where the traction/braking forces (tare, all cars motored) increase by approximately 100%.

Additionally, when motor cars accelerate through section gaps power is lost and they no longer provide traction to the train, this results in a further increase in coupler forces as the remaining motor cars compensate. While this occurs with both six and seven car formations, the additional mass of the special trailer car increases the peak coupler force to around 90kN at the UNDM / Special trailer coupler.

With the introduction of the ATO there was also a change in the maximum acceleration rate (although the rate is reduced for heavily loaded trains), this change in the rate of acceleration rather than the ATO itself resulted in a further reduction of fatigue life of the longitude.

As the relationship between stress and fatigue damage is not linear these increases in coupler forces due to the introduction of the special trailer (and to a lesser extent with the introduction of ATO) have a disproportionate impact on fatigue life and is the reason why widespread cracks are being found on the Jubilee Line and not the Northern Line at this time.

A total of 6 in service strain gauge tests were completed as part of this investigation in a number of different scenarios, such as through peak service, out of service, manually driven and on a Northern Line vehicle.

While there are a significant number of variables that can affect fatigue life in this arrangement such as inter-car position and build quality it is considered that the Special trailer (D end) under 2019 service duty has a fatigue life in the region of 2.25 years (meaning 2.3% of the population would initiate cracks in this time although they may not be detectable under the current inspection process) according to the fatigue analysis methodology provided in BS 8118 “Structural use of Aluminium”.

An out of service strain gauge test was completed at the UNDM / Trailer position on the Northern Line which had a calculated fatigue life of 11 years. While there are a number of differences between the fleets which would impact fatigue life it is considered likely that the original 96TS in its original six car formation would have a similar magnitude fatigue life (under the current 2019 service duty) and would not have achieved the 36 year minimum requirement.

The forces at either end of a coupler will be the same and therefore the same fatigue damage should accumulate on each intermediate end. From this it would be expected that the L14 manufactured cars would have slightly higher level of cracks, however this is not the case at either end of the special trailer car or for the 4 additional trains. While the reason has not been fully established there are concerns that these cars have not been built to the same standard which has further reduced their fatigue life.

The 96TS carbody structure was designed and gained first stage structural approval via Finite Element Analysis (FEA) in August 1994. Due to computational limitations at the time the FEA model could not accurately represent the geometry of the coupler support bracket but the model also made several assumptions regarding the application of the coupler loadcases which were at variance to the final design.

While the model was unconservative it did clearly highlight increased stress in the longitude at the bracket interface, but these positions were not included within the carbody strain gauge test even though many assumptions in the coupler area had been made.

There were several significant changes regarding the design and positioning of the coupler support brackets to meet the crashworthiness requirements such as positioning and bracket stiffness, the impact of these changes on the carbody structure were not adequately investigated.

The position of the coupler support bracket is directly across the headstock to longitude weld which would cause difficulty in maintaining a flat interface due to likely deformation and build-up of residual stresses on fabrication. To maintain flatness on manufacture a tolerance of 0.5mm was specified, this flatness was not met on all three of the longitudes measured. Bolted interfaces like that between the coupler bracket and longitude require a very flat interface otherwise it could result in bending of the I beam flange increasing stress in the web flange radii and at the fixing position.

There are also concerns regarding the consideration of Heat Affected Zones (HAZ) within the analysis of the carbody structure against the proof requirements. The carbody strain gauge test report did not make any commentary on a proof fail within a HAZ (reserve factor 0.7) at the longitude to tertiary headstock weld which has since been corroborated by in service testing (reserve factor 0.52)

While not considered a key factor in the formation of fatigue cracks significant concerns were identified with the reliability and underlying functionality of the coupler release mechanism and its ability to always function correctly under collision conditions, CCSO 397 was raised to control the condition while the correct resolutions are identified.

Lastly, the 96TS drawbars and auto-couplers are similar in design to those used on several other LU stocks and are a well proven design, although it is not known to what loadcases they were assessed against. The forces being transferred by these coupler components on the 96TS are higher than recently measured on other stocks and therefore a potential to have a reduced fatigue life.

Conclusions

The root causes of the formation of the fatigue cracks in the 96TS longitudes are considered to be due to the following main factors:

1. Inadequate consideration of loadcase requirements to demonstrate “fitness for purpose” above those specified as a minimum by the customer in both the original build and the later capacity expansion projects resulting in a product with a short fatigue life.
2. Inadequate reassessment of key design changes both in the original design approval and the later capacity expansion projects to determine their impact on other critical components leading to substantial reductions in the carbody fatigue life.
3. Inadequate consideration of manufacturing limitations in the design of critical bolted interfaces and failure to control manufacture to the set requirements leading to locked in static stress and poor transfer of dynamic loads.

Recommendations

1. There should be a redesign and fleet replacement of the coupler support brackets to significantly improve the transfer of coupler loads into the carbody structure.
2. The design of the inner longitude should be reviewed in conjunction with recommendation one and rectified to remove the risk of continued fleet wide crack propagation and to ensure the proof requirements are met.
3. LU Standard requirements with S1-180 and S2-180 should be reviewed with respect to:
    - The coupler fatigue loadcase requirements on the carbody structure and coupler assembly.
    - The requirements for contractors to demonstrate all derived loadcases essential to demonstrate fitness for purpose.
    - The impact assessment requirements for design changes within projects and how the interfaces between contractors are managed.
    - Flatness requirements for critical bolted interfaces.
4. That a full carbody finite element analysis of the 95/96TS bodyshell should be undertaken together with any additional testing required to determine any other underlying risk prior to failure.
5. The fatigue life of the longitude on the Northern Line should be investigated in more detail to determine what mitigation activities could be taken to limit the impact to service and any future repair cost.

6. Review the current acceleration requirements through section gaps and regenerative to friction braking blend on 96TS to limit the loading requirements on the future permanent longitude repair.
7. The 96TS coupler release system should be replaced at the next overhaul to ensure it will always correctly function in a collision scenario and eliminate the current costly maintenance burden on the depot.
8. The findings of this report are distributed to current new rolling stock projects such as DTUP.
9. Complete fatigue assessments of the 96TS auto-coupler and drawbars and review the quality of manufacture at critical locations.

2. Background

In Oct 2019 fatigue cracks were found in the Jubilee line fleet's inner longitudes that support and transfer loads from the coupler and drawbar arrangements to the carbody structure. Checks on other cars were immediately put in place and trains with the most significant cracks removed from service. An inspection programme was established to mitigate the risks and the cracks divided into four categories (CAT 1 - Stopped, CAT 2 – Stopped until Plate repair competed, CAT 3 NDT every 10 days, CAT 4 NDT every 28 Days) as well as a full fleet inspection every 3 months. A temporary repair programme was also put in place and the vehicles returned to service in a controlled manner to allow time for a permanent solution to be generated.

An investigation to determine the key factors which caused the cracks to occur was completed by LU RS Mechanical Engineering team with the support of JNP Fleet / Fleet engineering and TFL Engineering Technical Services. This report brings together the key conclusions and recommendations of the wider investigation, which is contained in seven key LU engineering reports references 1 to 7 in section 16.

The report provides a brief overview of the relevant history of the Jubilee Line trains, a description of the train formation and coupler arrangements, and a review of the original structural analysis and testing of the coupler and carbody in sections 3 – 7. Sections 8 and 9 summarise the impact of the introduction of the special trailer cars and the implications of the design and manufacture of the coupler/carbody interface. Sections 10 – 12 provide analysis output from recorded crack data and service testing, while sections 13 and 14 consider the relevance of known failures of other components in the coupler system. Conclusions are provided in section 15.

While the investigation has tried assess all the relevant details to inform the conclusion it makes, it is considered likely some important documents may not have been available due to the span of time the investigation covered and therefore some statements may require adjustment if further evidence is found

3. History

The Jubilee Line trains, known as the 96 Tube Stock (96TS) were purchased as part of the Jubilee Upgrade Project. Due to the line expansion and connection to the developing Canary Wharf site it was envisaged that the passenger numbers would increase over time. To cover this scenario the contract was for a six-car train with the option of a seventh trailer car formation. It was also originally intended for the fleet to operate in a form of automatic train operation (ATO), but this was not implemented at the time due to technical issues.

The key milestones in the development of this vehicle type relevant to this investigation are as follows

- L14 Project (1997/8) - Original delivery of 96TS trains in six car formation.
- L17 Project (2006) - Delivery of 96TS special trailer cars (SpT) (seventh Car) and additional 4 trains entered.
- L19 Project (2011/12) - Upgrade of 96TS to Automatic Train Operation

- L15 Project (1998 -2001) - Original delivery of 95TS trains – The Northern Line trains are very similar in construction to 96TS and approval was based in part on L14 Project

4. Train formation and Coupler Arrangements

The Jubilee line tube stock was originally made up of two 3 car units comprised of two motored cars a Driving Motor (DM) an Uncoupling Non-driving Motor (UNDM) and one Trailer car (T) and resulted in a 67% motored configuration. This was later (~8years) converted to a seven-car formation with the addition of a special trailer (SpT) to make one four car unit that was 50% motored, (Figure 1)

The design of the carbody structure and the coupler assembly is the same at all inter-car positions except that drawbars are used between cars and auto-couplers are used between units; these will be referred to as couplers within this report. The carbody structure at cab positions is not affected by this issue as it takes no load under normal service operation.

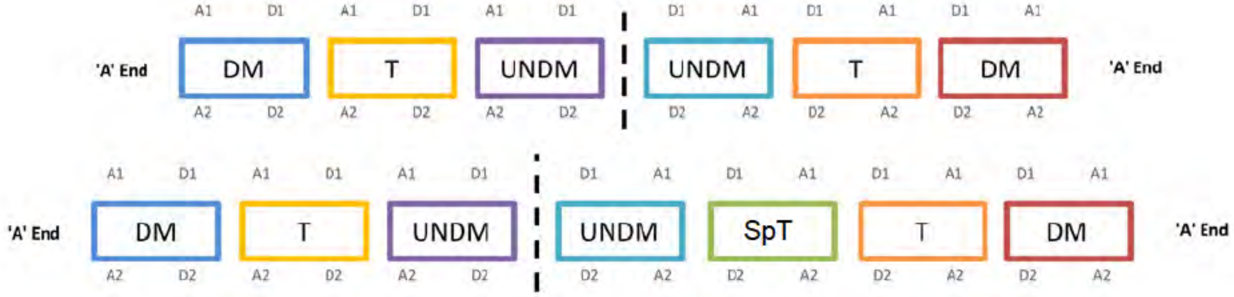

Figure 1, 96TS six and seven car formations

The inner longitude is an extruded aluminium I beam which is welded in position at either end and to the floor extrusion. At one end it is connected to the aluminium inner headstock via a horizontal weld, (Position W). This weld is situated directly across the bolted interface of the coupler support bracket. Longitudinal acceleration and braking forces are transferred from the coupler through the drawgear (which comprises rubber elements to dampen the force input) and into the carbody via the coupler support brackets. Figure 2

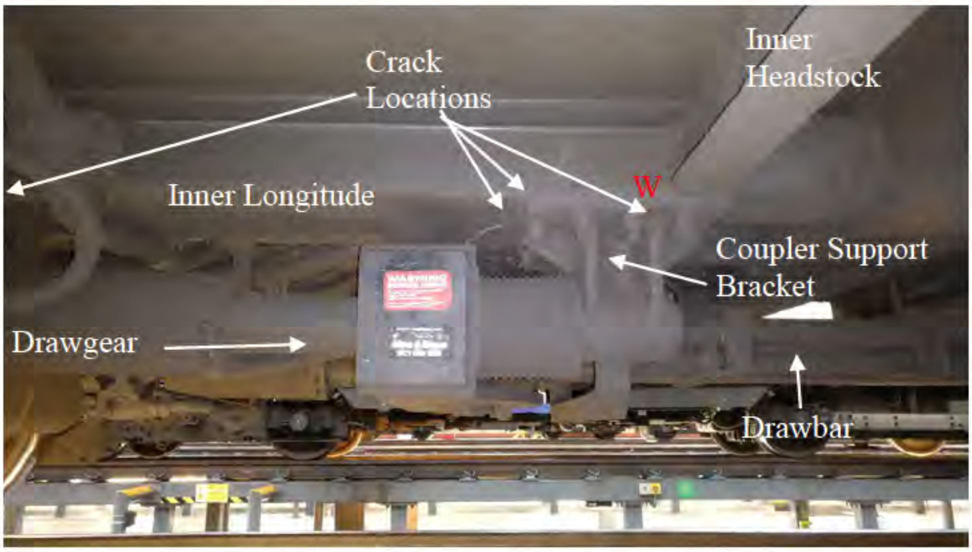

Figure 2, 96TS Coupler assembly and carbody structural arrangement

5. L 14 Coupler Assembly Structural Assessments

The coupler assembly (including support brackets) was originally supplied by Radenton. As the OEM they were responsible for delivering a product that met the structural and functional requirements.

The L14 Particular Specification [Ref 8] defines a number of mandatory structural requirements for the couplers and the vehicle crashworthiness. The relevant (abridged) requirements being:

- The Wedgelock Autocoupler shall withstand a tensile load of 500kN without parting (Customer specified clause 8.6.3.1)
- Impacts of up to 3km/h – The drawgear will absorb the impact energy by 'elastic' recoverable compression of the rubber springs (Customer specified)
- Impacts at between 3 and 10km/h – The generation of force greater than a 3km/h impact will result in the operation of the collapse elements within the drawgear and engagement of the anti-climber. (Customer specified and results in the compressive loadcase below)
- Impacts at above 10km/h – Further energy absorption will be provided by progressive collapse of the car end structures (Customer specified)

This resulted in the L14 project proof load requirements of 400kN Cab end and 350kN intermediate end (compressive) and 500kN (tensile) for the coupler. The compressive loadcases are derived to represent a light collision (+3km/h prior to coupler retraction) as part of the crashworthiness assessment, which were based on the seven-car formation.

During the design and testing phase of the system there were several design changes made to the coupler support bracket and the proof force requirement which are detailed within the Submission for couplers [Ref 9]

- The initial concept design reviews were completed based on an aluminium coupler support bracket. Believed to be drawing: R5200 Bracket (intermediate end only) Nov 1994.
- The first static coupler test (26/06/95) was completed on a steel bracket, this test was against lower force requirements; 155kN compressive Intermediate end (178kN cab), 262.5kN tensile. The test "passed" with measured stress of 404N/mm^2 against an applied force of 270kN with minimal permanent set. The fabricated steel bracket had a material yield of 355N/mm^2. Drawing: (Sk85 / 107) Steel Bracket – Fabricated with a 15mm longitudinal gusset (Jan 1995)
- The Carbody Strain Gauge test resulted in a failure of the Radenton supply coupler support brackets, the report [Ref 10] section 6.4 stated that they were subject to redesign due to high stresses seen on the carbody static test under a 400kN compressive loadcase.
- The submission also provides a copy of a repeat static test specification (but no results) on the coupler support brackets to 400kN compression (Cab end requirement) and 525kN tensile. This test sought to demonstrate the acceptability of the fixing arrangement in the event of a collision and the coupler was to be attached to a representative longitude. Presumed to be drawing (R5202 LH / R5203 RH) Steel Bracket - Cast + Fabricated with a

30mm Longitudinal gusset (1995)

No details of any fatigue testing for the coupler support brackets were identified within our review.

6. L 14 Carbody Structural Assessment by Finite Element Analysis (FEA)

The carbody FEA report [Ref 11] was reviewed regarding its assessment of the coupler loadcase requirements.

Within the design assumptions section 2.1.2 it states that the loadcases are as described with the customer specification with additional "derived" loadcases which arise from the operation of equipment e.g forces generated by the coupler and anticlimber collapse.

The most applicable coupler loadcases applied to prove the carbody structure were:

- 200 kN compressive and tensile applied to the coupler mounting point in the extreme laden condition (customer requirement within the specification Contract 201 clause 8.4.2.1)
- 400kN compressive force applied to the coupler mounting point in the crush condition (Derived to represent light collision – prior to coupler retraction)

No 500kN tensile proof coupler loadcase was applied to the carbody structure even though it was a proof requirement for auto-couplers to withstand this force without parting.

No carbody fatigue assessment was made considering the resultant forces in the coupler from acceleration and braking in service in either the six or seven car formations (which is the current mode of failure causing cracks to form). While this loadcase was not an explicitloadcase within the specification, it would fall under the requirement to complete structural assessment (including fatigue) where failure would lead to an incident such as derailment or substantial maintenance costs or damage, [Ref 8, (Appendix 2)]

The FEA is comprised of a ¼ shell model and due to computational limitations at the time did not accurately model geometry in all areas; the application of coupler loads is one such area with the generation of a "Dummy Bracket", the model also has a limited number of elements due to processing power, Figure 3.

Figure 3, FEA "Dummy Bracket" compared to current coupler support bracket arrangement

As can be seen from the model the "dummy bracket" is located wholly on the longitude flange and not from the front of the inner headstock as in the final design. Having the bracket so far to the rear of the much stiffer headstock and collapse tube is likely to have a significant impact on the validity of the results.

No specific details of the "dummy" bracket are provided, however considering the 1994 approval date and the results it is considered likely that this is modelled with aluminium properties. The green elements are also presumed to represent the bracket base which extend past the rear bracket web (in an irregular arrangement) allowing smoother transfer of loads into the carbody structure than occurs in the final design. Additionally, no fixing holes are represented and their effect on stress has not been considered. The longitude is made from 6082-T6 with a 0.2% proof strength of 260N/mm^2 which has a Heat Affected Zone (HAZ) strength of 130N/mm^2.

As can be seen from the results for the 400kN compressive loadcase (Figure 4) the longitude peak stress of 97N/mm^2 was located at the rear weld connection to the tertiary headstock. No results are shown for the bracket as this was only generated to impart the load on the carbody structure, however the peak stress would be expected at the base of the rear web (point X). This is inboard on the bracket (green elements) so allows distribution of the load into the carbody structure in a way that does not occur on the final bracket arrangement.

The model predicts a stress of around 70N/mm^2 at the bracket / longitude interface - well within the material yield, however with the number of assumptions that have been made in the model construction the stress pick up either side of the bracket would have been noteworthy and should have warranted further assessment in physical testing.

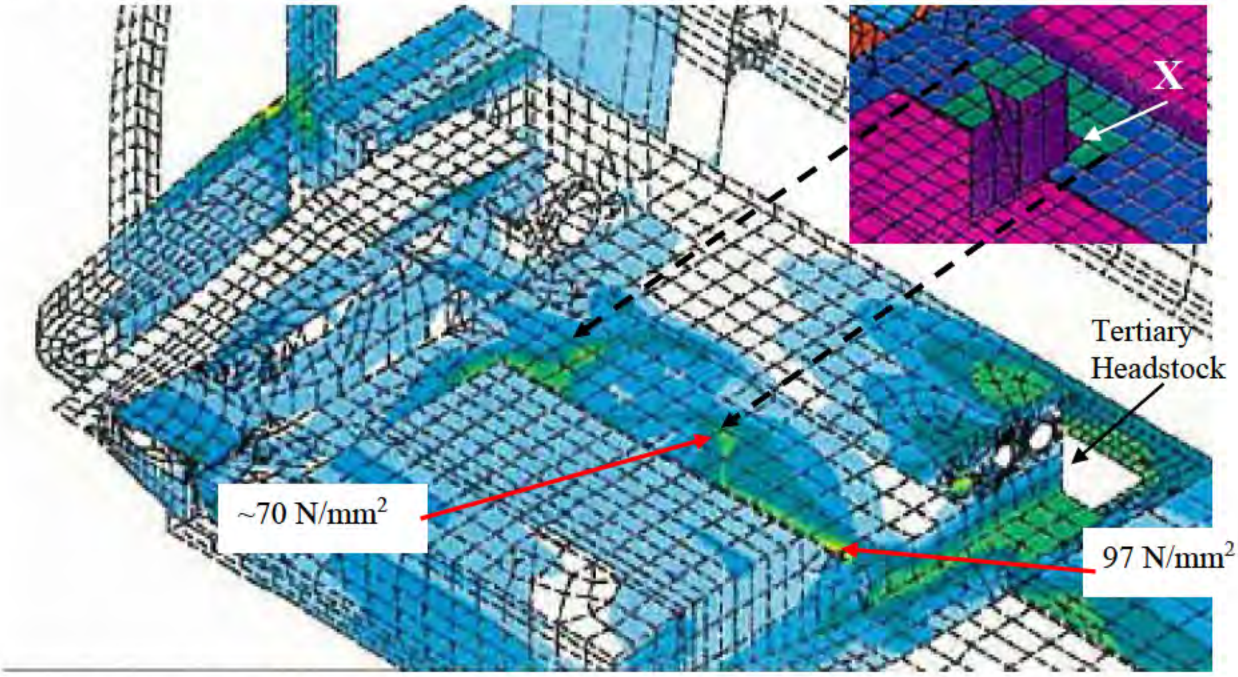

Figure 4, 1994 FEA results for 400kN couple compressive loadcase – intermediate end

Further details of the review of the carbody FEA can be found in [Ref 1]

7. Carbody Static Strain Gauge Testing

Following completion of the carbody FEA the results were used to identify key stress locations to help guide the positioning of strain gauges on the static carbody test (date 29/03/95). This is covered in Report [Ref 10].

For the coupler loadcase requirements eight strain gauges were fitted to the cab end coupler bracket and nine at the intermediate end longitude connection to the tertiary headstock. No gauges were fitted to the front or rear of the coupler support bracket at the intermediate end to identify stress associated with the interface between the coupler support bracket and longitude.

The most significant coupler load test completed was a 400kN compressive force in the crush and extreme laden condition. This force was applied to the cab coupler support brackets and reacted at the intermediate end coupler brackets. No tensile loadcase was applied.

It is difficult to determine the exact location of the nine strain gauges fitted to the longitude or the tertiary headstock due to our low-resolution scanned copy of the photographs and having no record detailed within the report.

All but one gauge recorded very little stress with the applied coupler loadcases except Strain Gauge 247 labelled as "Tertiary headstock to longitude connection; trailing end; south side" which registered a stress of -169N/mm^2 (No photo of the gauge is provided). This is noted elsewhere in the report as having a permissible stress of 130N/mm^2 indicating this is within a weld heat affected zone (HAZ). No commentary is made regarding this value even though this would be considered a fail with a reserve factor of 0.77.

As previously discussed, high stresses were identified on the coupler support bracket within this test and it was subject to a redesign by Radenton at the time of report generation. There is no reference to or photographs of the location of the intermediate end coupler support bracket, so it is not possible to determine its exact location on the longitude.

The final design of the coupler support bracket has an increased gusset thickness from 15mm as per the static load test to 30mm. The bracket gusset is positioned centrally on the bracket to transfer the load directly into the Longitude I beam web however such a significant stiffening of the bracket will clearly have a negative effect on the I beam stresses.

Further details of the review of the carbody strain gauge test can be found in [Ref 1]

8. Impact of Introduction of the Special Trailer and ATO

In 2006 as part of a capacity increase an additional car (Special Trailer) was added to one unit of each train and 4 new trains were purchased. From the L17 project assurance plan it is clear there was an aim for the vehicles to be as close to the original design as possible at the request of the customer. This was to maintain compatibility of design and maintenance and the design submission focused mainly on where variances occurred. Between the L14 and L17 projects Voith had taken over Radenton and became the “Original Equipment Manufacturer” (OEM) and supplied the L17 couplers.

From the design submissions for couplers the assurance philosophy was based on previous approval of the Radenton design within the original L14 approval and proven service to date. It should be noted that a coupler release failure mode was know prior to the project. The same design was provided which resulted in a number of early failures post-delivery, discussed in section 13.

The Final Design Submission for Bodyshell [Ref 12] uses the same philosophy that design compliance was demonstrated on L14 vehicles and the design material and manufacturing process on the special trailer cars are the same as the previous L14 vehicles. No additional coupler loadcases are identified against requirement clause 8.7.2 regarding *‘Any loadpath not modelled or changed from the existing cars shall be identified and assessed to verify structural capability’*.

There was a general belief that the coupler arrangements were designed for the seven car formation as part of the L14 project which is correct in respect to the crashworthiness calculations, however as can be seen there was no coupler forces fatigue assessment completed on either a six or seven car formation and therefore this has also not been considered as part of the L17 upgrade.

In 2012 a second major change to the stock was made with the introduction of Automatic Train Operation (ATO) through the introduction of a Transmission Based Train Control (TBTC) system.

Prior to its installation there was a concern raised by LU that its introduction would lead to increased acceleration and braking frequencies which in turn would result in a greater number of fatigue cycles on the car body.

A report was issued detailing the assessment into the effects of implementation of TBTC on car body stress to close out the concern [Ref 13].

The primary conclusion was that the maximum predicted fatigue damage (RF 0.81) remained below a RF 1.0 and therefore the recommendation was that the bodyshell did not require further analysis to demonstrate that it is acceptable with the introduction of TBTC.

It is recognised within the report that traction and braking forces were not considered within the L14 submission but an argument is constructed why they are still not required rather than completing the analysis. The report reviews the main loadcases within the L14 submission including a 3g longitudinal proof acceleration for attached equipment. It also concludes that the increase in fatigue cycles is directly proportional to the increase in mileage due to timetable changes associated with TBTC introduction. Further analysis is presented to show the 15% increase in mileage would not impact the carbody fatigue life.

As part of the current investigation an in-service test was completed with manual driving and compared to an equivalent one in ATO. While the number and size of coupler forces seen due to manual driving were slightly lower than with ATO, the difference was marginal and it was therefore clear that the resultant force in the coupler is directly proportional to the rate of acceleration and deceleration of the train.

Since introduction the maximum traction acceleration rate has changed twice.

- L14 (1998) Stock Introduction - 1.12m/s^2
- L17 (2006) with the introduction of 7th car reduced to 0.98 m/s^2
- L19 (2012) Introduction of ATO increased to 1.2 m/s^2 (although reduced if the train is heavily laden).

The theoretical forces in the coupler due to these accelerations (all driving cars motored, tare condition) were modelled including the change in train formations to provide an insight into the likely impact of the changes made. Table 1.

	6 car		7car	
Dates		~1998 to	~2006 to	~2012 -
Stock / Project	(95TS)	(96TS) L14	(96TS) L17	(96TS) L19
Acceleration (m/s^2)	1.3	1.12	0.98	1.2
Maximum Force kN	15.47	13.328	27.02	33.09
Coupler location	UNDM / T	UNDM / T	UNDM / SpT	UNDM / SpT
% increase	-	-	103%	22%

Table 1: Highest coupler force (4 cars motored) for each train formation

As can be seen the introduction of the special trailer car (reducing one unit to only 50% motored) had the most significant effect, more than doubling forces even with a reduction in the rate of acceleration. The forces are further increased by up to 22% on the L19 project with the increase in the rate of acceleration i.e. approximately 2.5 times higher than those associated with the original 6 car formation. The relationship between load range and stress range is linear but the relationship between fatigue life and load or stress range is not. A doubling of load range will reduce fatigue life by a factor of at least 8; a factor of 2.5 will reduce fatigue life by at least 15.

Further details of the review of the impact of the L17 and L19 projects on carbody life can be found in [Ref 1] & [Ref 2]

9. Design and Manufacture of Coupler Bracket / Carbody Interface

As per the L14 FEA it is possible that the original design concept was to have the coupler support bracket situated entirely on the longitude which would have resulted in a reasonably flat interface, however the coupler support bracket is now aligned with the front of the headstock.

In this position the bracket straddles the headstock longitude weld which is considered a significant risk in maintaining a flat interface due to likely deformation of the both the headstock and longitude when welding. This can also build in residual stress around the joint. The concern would be that on assembly the weld line would create a pivot resulting in bending of the aluminium I beam downwards to meet the flat steel support bracket under bolt preload, Figure 5. Since the I beam web is very stiff vertically, this deformation would occur primarily in the flanges.

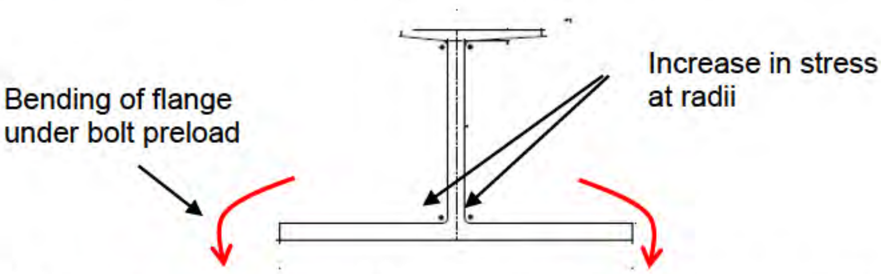

Figure 5: Bending of Longitude I beam under bolt preload on non-flat interface

The intermediate end drawings [Ref 14] requires that a flatness tolerance of 0.5mm should be maintained at the joint between headstock and longitude and that the weld should be ground flush in a longitudinal direction. There is a further tolerancing drawing referenced but not seen by this investigation.

This interface was measured on three cracked longitudes (side 1 and 2) and all three were found to fail the flatness requirement at the weld joint between the longitude and headstock on at least one side, Table 2.

Category	Unit	Location	Gap with feeler gauge
CAT 2	96661	Side 2 A-end	0.75mm
CAT 2	96661	Side 1 A-end	1.2mm
No crack	96461	Side 2 D-end	<0.05mm
CAT 1	96461	Side 1 D-end	0.75mm
CAT2	96479	Side 2 A-end	<0.05mm
CAT1	96479	Side 1 A-end	4.5mm

Table 2: Measured flatness across coupler support bracket interface

The arrangement has a total of 10 x M16 bolts grade 12.9 torqued to 230 Nm, 4 on the headstock and 6 on the longitude. The contact points between the bracket/longitude can be seen clearly on the headstock and longitude due to the darkened regions in the dissimilar material barrier material, the main contact points being the edge of the headstock radii, headstock fixings, weld line, longitude web rear of weld line and longitude fixings, Figure 6.

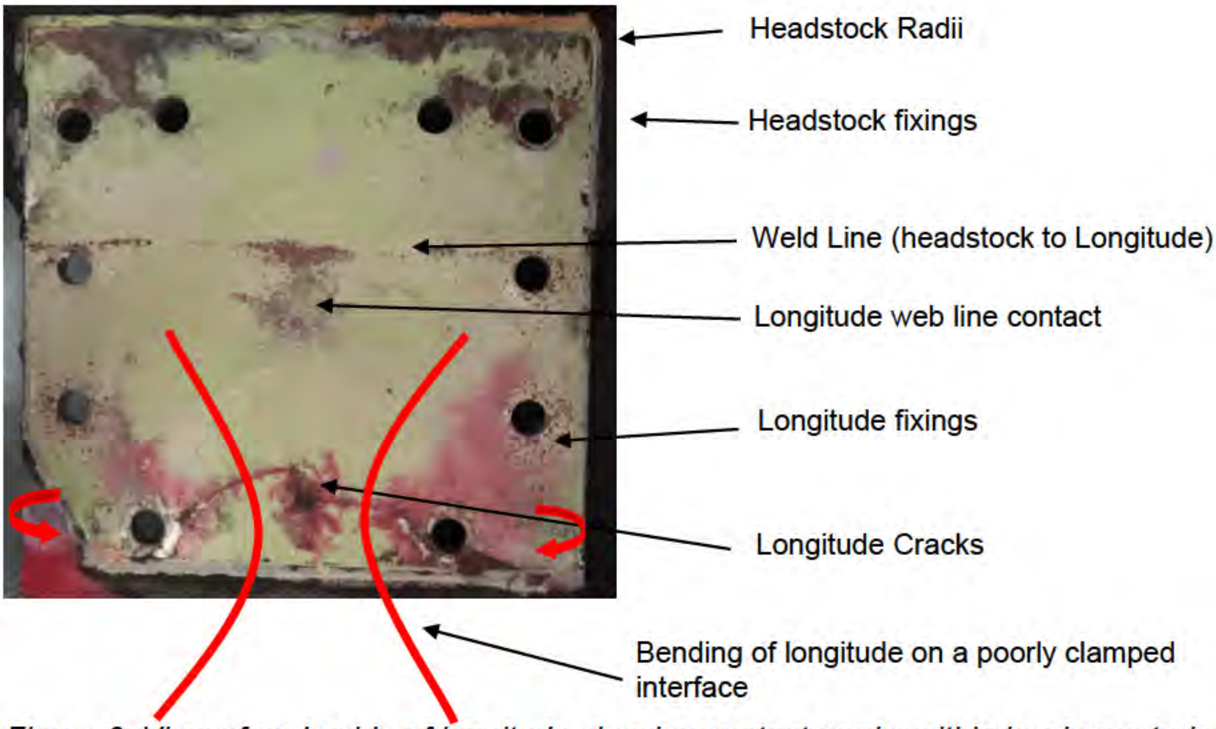

Figure 6: View of underside of longitude showing contact marks within barrier material

When acceleration and braking forces are transferred through a poorly clamped coupler support bracket this can result in further bending of the longitude flange rather than transferring the load through the correctly compressed joint into the longitude web, this bending is centred around the rear fixing holes due to the large change in stiffness between the steel bracket and aluminium longitude.

An FEA model was generated to further understand the impact on stress location and magnitude on a poorly clamped interface. The first analysis was a perfectly flat interface with full contact between the bracket and longitude and restrained at the fixing holes. The second attempted to represent the non-flat interface by removing the contact face on the longitude but not the headstock, this transfers the load from the longitude web to the flange

Neither model fully represents the actual position so the focus should be on how the stress positions change and the actual values ignored, Figure 7.

Representing a flat interface with loading in the longitude web as per design intent

Non flat interface with loading in the longitude flange

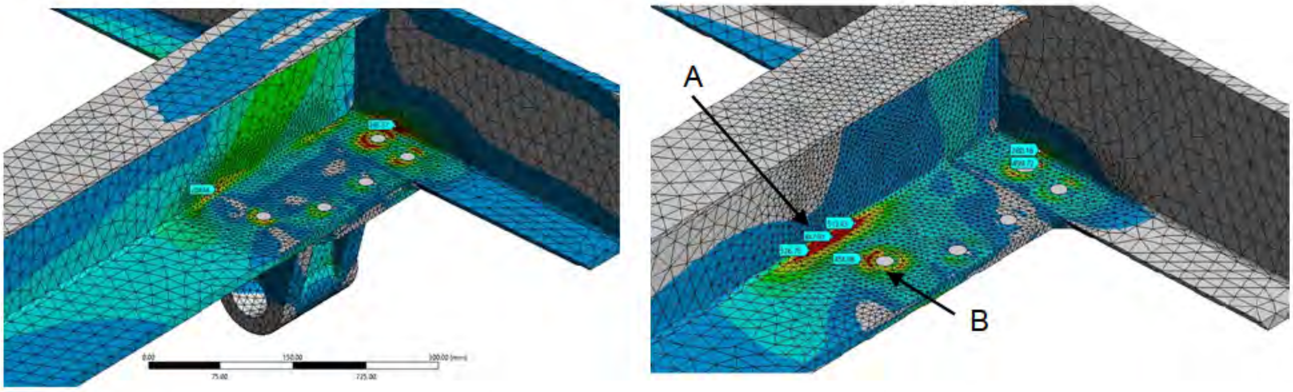

Figure 7: FEA representations of flat and poorly contacted interfaces at the coupler support bracket

As can be seen transferring the load though the flange rather than the web has a significant impact on the stress magnitude and location due to bending and results in high stress at the two main crack initiation locations at points A & B.

Further details of the of the design and manufacture of the inner longitudes can be found in reports [Ref 2], [Ref 3], [Ref 4]

10. Crack Data

A review of the cracks which have been identified through NDT shows there are two main locations where cracks initiate in the longitude to the rear of the coupler bracket interface, points A & B. The cracks at (A) initiate at the flange to web radii and propagate in an arc in both directions. The cracks at (B) initiate in the vicinity of the rear fixing hole and propagate laterally across the flange. As B style cracks initiate on the underside of the flange these can grow to several cm before they propagate through the flange thickness and can be seen by NDT inspection meaning that the full extent of cracks will not be identified until brackets are removed during overhaul or repair, Figure 8.

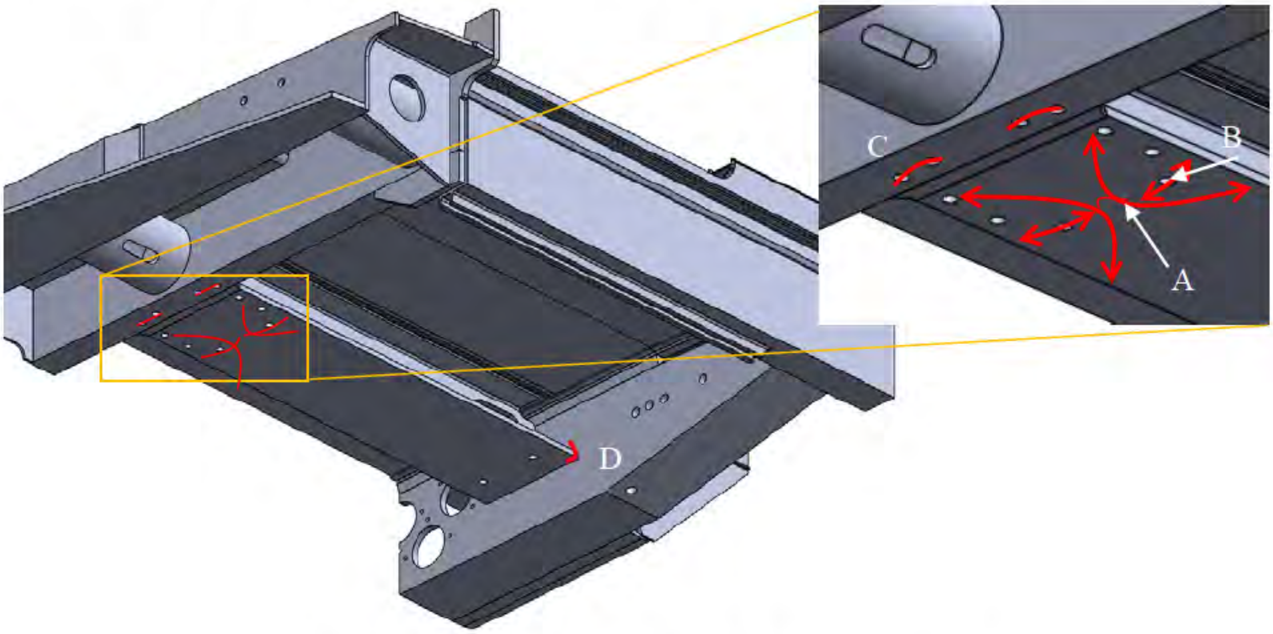

Figure 8: Carbody inner Longitude crack locations

Cracks have also been identified at two other locations: at the headstock bracket fixings holes (C) - these cracks have only been found in conjunction with CAT 1 cracks or have grown to a detectable size due to increased stress in this area as part of the repair process; the fourth crack location being at the weld of the longitude flange to the tertiary headstock (high stress area identified within the original FEA). Only a very small number of cracks have been found at locations C and D and are not covered within the following data review.

The main cracks can form on either side of the flange for each longitude which means that there are up to 8 crack initiation points per car end. Only the worst crack at each car end is considered within the data.

The cracks were divided by severity into four categories with CAT1 being the most severe. A review of the distribution of the crack severity (worst per car end) shows that most cracks are located at the coupler between the UNDM and special trailer (X), Figure 9. This is not surprising as this location is the highest loaded, however the crack distribution is not fully as would be expected if the cracks were being driven by coupler force alone.

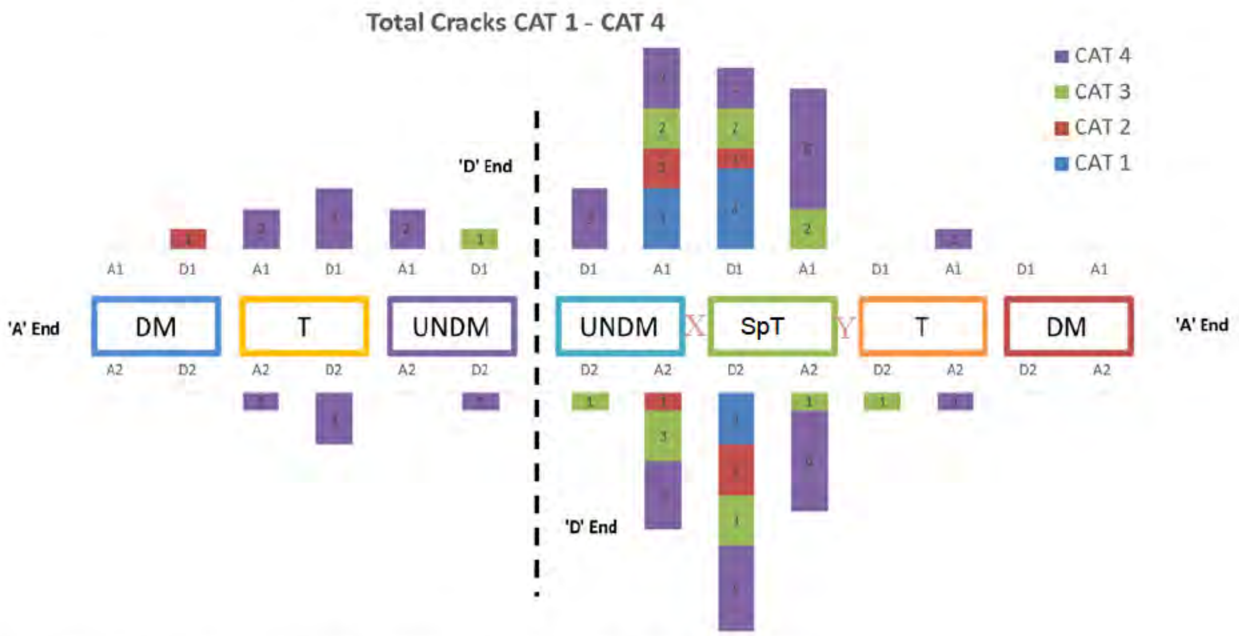

Figure 9: Crack location and Category (data up to 14/05/2020)

The reaction at the coupler brackets due to non-transient forces though a coupler will be the same at both ends and therefore should accumulate equal fatigue damage. In the original 6 car formation the 4 car UNDM was connected to the Trailer car, this location between stock introduction and 2006 (8years) was the highest loaded position accumulating fatigue damage during this time (although at a significantly lower rate of damage accumulation).

Since 2006 the UNDM A end (X) and the Trailer D end (Y) should have accumulated equal damage to the corresponding end of the SpT car, meaning that the number and severity of cracks on the (L14 manufactured) UNDM A end and Trailer D end should be slightly worse than that seen on the (L17 manufactured) special trailer. This is not the case on either car which indicates that the L17 special trailer car is more susceptible to fatigue cracks than its equivalent L14 manufactured car.

The L17 manufactured vehicles susceptibility to cracks can also be seen when reviewing the crack data for the 4 additional trains purchased at the same time (ignoring the SpT cracks), where 29% (7 off) of the L17 manufactured cars have cracks compared against only 8.5% (30 off) of the L14 cars have cracks even though they have had 8 years additional duty (although at a lower rate of damage accumulation), Table 3.

	L14 cars	L17 cars (excluding ST)	Special Trailers
Fleet Total	354	24	63
Percentage Cracked	8.5%	29.2%	65.1%

Table 3: Percentage of cracked cars by project delivery

Crack Growth

The cracks were first identified in October 2019 and have been regularly checked by NDT since (data until May approximately 7 months). As in any NDT crack monitoring regime there are fluctuations in measurement data. Removing any obvious inconsistencies, the crack growth data for category 3 and 4 cracks was established, Table 4.

	Max growth / day	Average for cracks with growth	Average all of Category
CAT 4	0.24 mm/day	0.1 mm/day	0.03 mm/day
CAT 3	0.32 mm/day	0.23 mm/day	0.11 mm/day

Table 4: Crack growth – Categories 3 and 4

Over approximately seven months only 13 of a total of 43 CAT4 cracks propagated at all (30%); this is not uncommon as cracks can have periods of stability followed by crack propagation due to the material structure. Crack growth initially starts slowly and increases as the area of material supporting the load reduces increasing the stress at the crack tip. From the CAT 4 growth rate it is evident that it would take many years to reach the current fleet condition. However, cracks on the SpT's and the 4 car UNDM will be propagating at a quicker rate than the averages as the higher forces will increase the growth rate.

Further details of the analysis of the crack data can be found in [Ref 5]

11. Carbody Proof Load – Derived from Service testing

Strain Gauge Calculated Proof Load – Intercar End (Parent Metal)

As part of the investigation strain gauge tests were completed which also measured the coupler forces. The relationship between force and stress was shown to be linear (Table 5) and therefore the intermediate end longitudes' ability to meet the proof load requirements can be calculated. The table below details derived stresses against a given force at crack initiation point A. This shows the longitude would pass at 400kN compressive but would fail the 500kN tensile loadcase with a reserve of 0.86

kN	Load Description	N/mm^2	Reserve Factor
350	Coupler Release (Intercar)	211	1.22
400	Proof compressive	241	1.07
500	Proof tensile	301	0.86

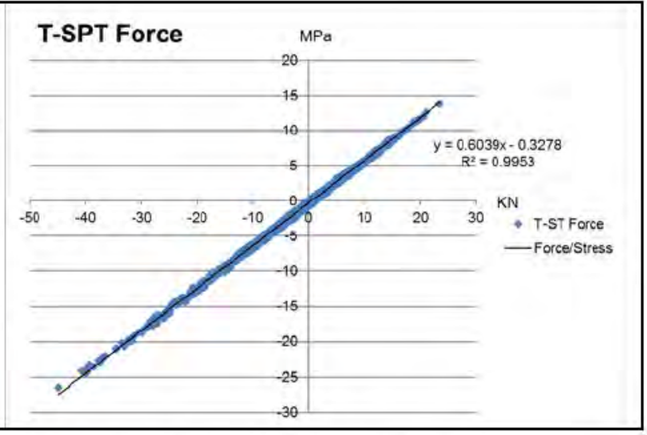

Table 5: Parent metal proof reserve factors against loadcases

Strain Gauge Calculated Proof – Intercar End (HAZ)

The exercise was repeated for a gauge positioned at the weld connection between the longitude to the tertiary headstock (crack location D). (The wider data spread is believed to be due to the gauge's position near the tertiary headstock and is therefore also affected by passenger loading). As can be seen the HAZ did not meet any of the proof loadcases in agreement with the carbody static test results in 1995, Table 6.

kN	Load Description	N/mm^2	Reserve Factor
350	Coupler release (Intercar)	218	0.59
400	Proof compressive	249	0.52
500	Proof tensile	312	0.41

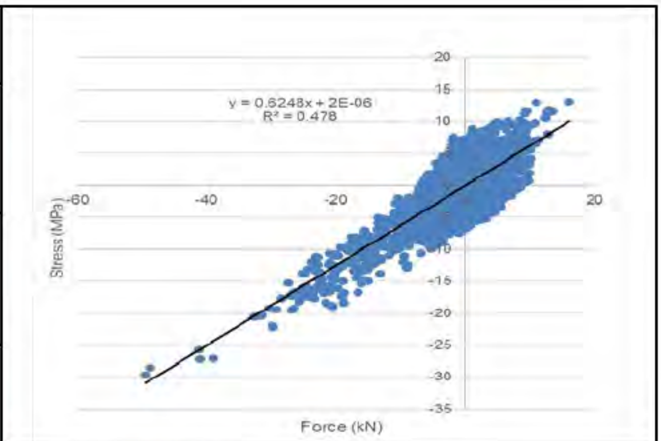

Table 6: HAZ proof reserve factors against loadcases

Further detail of the review of the proof requirements assessments can be found in [Ref 1] [Ref 2]

12. Fatigue Life assessments

As previously shown the theoretical maximum force due to the acceleration rate with 4 cars motoring would be 33kN. This would be at the coupler between the 4 car UNDM and SpT (X). However, when a train passes through a station (or other) section gap under acceleration, traction is lost on each motor car in turn. this has the effect of temporarily increasing the load though each coupler position in turn. The worst case remains at UNDM / SpT coupler position picking up much of the SpT, Trailer and DM loads when the leading DM car is gapped resulting in a theoretical compressive load of up to 85kN, Figure 10.

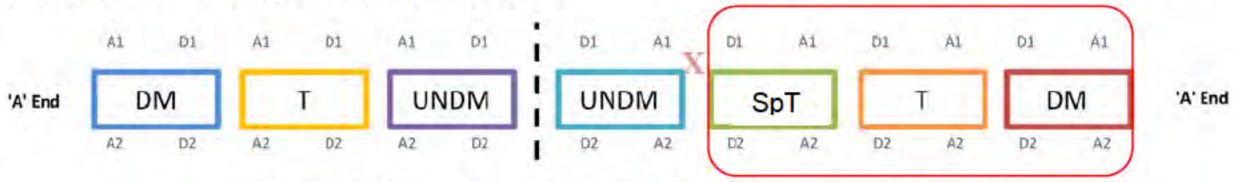

Figure 10: Seven car formation during gapping of 4 car DM

The fatigue damage accrual is solely driven by these same traction and braking forces distributed through the couplers under varying conditions, Figure 11. Negative forces are generally due to acceleration and positive due to braking, although as can be seen large inputs often result in load reversals due to the following motor car becoming gapped and a rapid reversal of load through the coupler.

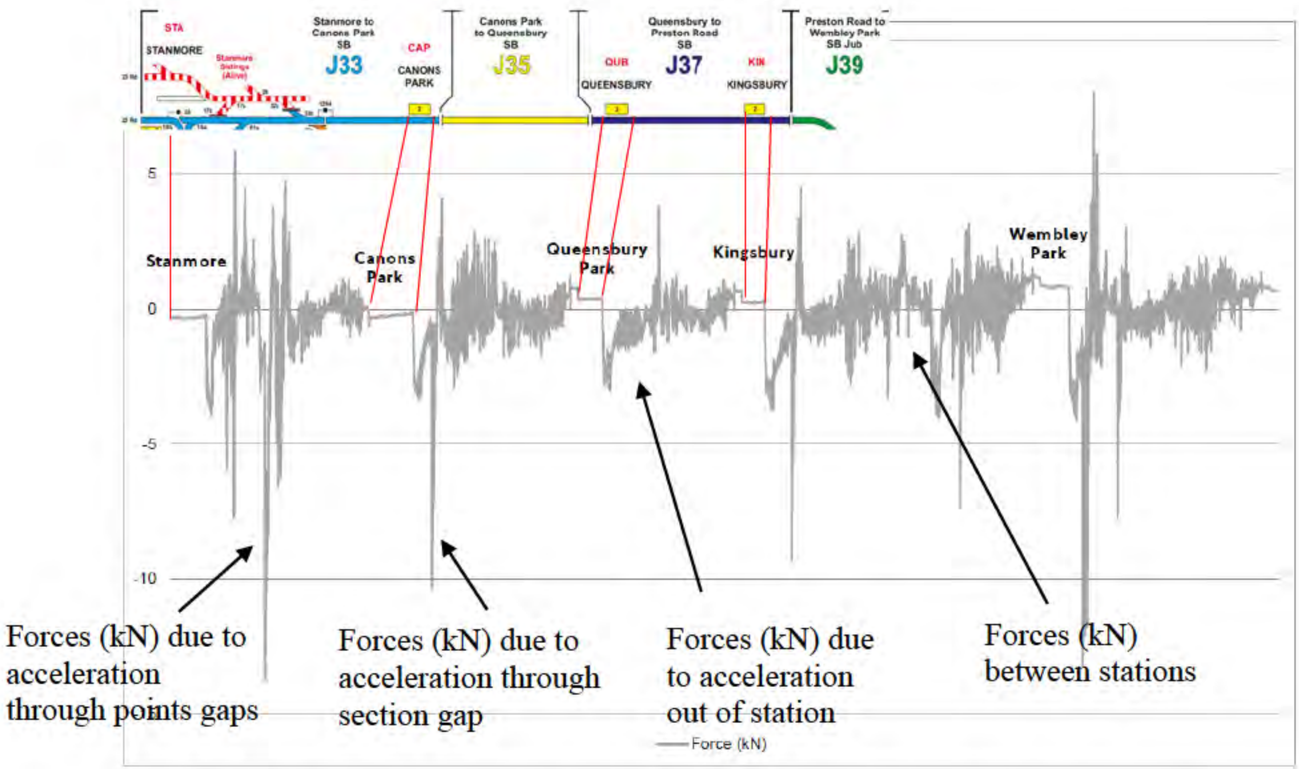

Figure 11: Coupler force(kN) between Stanmore and Wembley Park stations

A total of 6 strain gauge runs were competed as part of the investigation, these were taken on several different vehicles, coupler positions and under different driving conditions such as tare loaded, in ATO passenger service and manually driven.

Each test sought to identify the loading characteristics through the couplers and determine fatigue life calculations at different locations on the longitude and headstock.

The coupler force cycles for an ATO test in passenger service have been plotted as a histogram against the number of cycles to show the coupler force characteristics at the SpT – UNDM (Marked X), the SpT – T (Y) and T – DM (Z). As can be seen the SpT -UNDM has significantly higher forces and a greater number of cycles at higher magnitude which are driving the fatigue damage and increased crack formation, Figure 12.

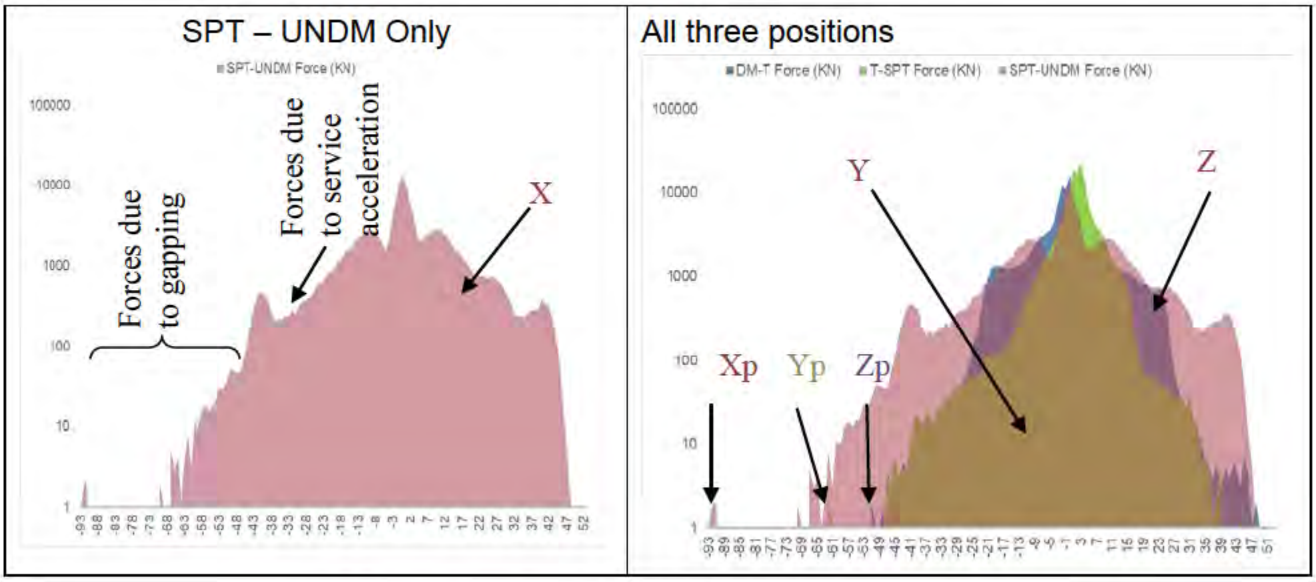

Figure 12:Histogram of coupler forces against number of cycles

The peak values identified during testing (Xp), (Yp) & (Zp) demonstrated a good correlation with the forces predicted which demonstrates that other factors such as track condition have little impact on the crack formation, Table 7.

Drawbar location	Max Force recorded (KN)	Max Force predicted (KN)
UNDM – SPT	93	85 (When 4 car DM is gapped)
SPT – T	68	60 (When either DM is gapped)
T - DM	53	46 (when both UNDMs are gapped)

Table 7: Comparison calculated and actual peak coupler forces

Fatigue Life Calculations

Due to the level of cracking on both the SpT and UNDM (X) it was not possible to directly assess the fatigue life at this position and following NDT checks a SpT / T position (Y) was chosen. All fatigue lives presented are for the lowest measured value which is at crack location A.

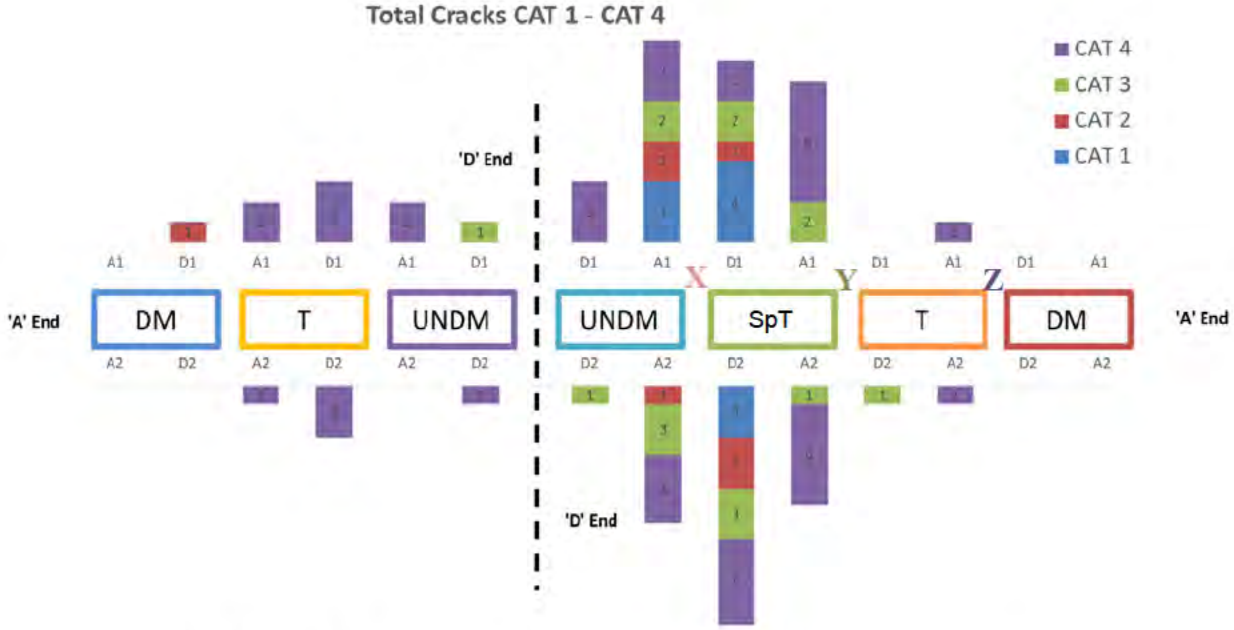

Figure 13: Seven car formation - cracks against coupler position

The Fatigue life on an L17 SpT (A end) under the force profile at (Y) was calculated as 8.7 years with a 2.3% probability of crack initiation. The adjoining trailer car (L14 Trailer D end) of the same design would normally be expected to have the same fatigue life, however as seen in the review of the crack data the L17 cars appear to be more susceptible to cracking and in this case the trailer car may have a longer fatigue life. This is supported by the fact that only one crack has been found at this location even though this car accumulated an additional 8 years of damage (although at a significantly lower rate of damage) prior to the introduction of the SpT car. (While only one crack has been found it is considered likely that crack initiation has occurred on other cars but have not yet been identified), Figure 13.

Using the linear force / stress relationship (shown in the parent metal proof assessment) the force rainflow for the coupler at (X) was used to derive a fatigue life at the D end of the SpT car of approximately 2.25 years. The same increased fatigue life argument for the (L14 T D end) above applies to the L14 UNDM (A end).

Several months prior to the cracking issue becoming apparent on the 96TS Alstom had identified fatigue cracks within the aluminium coupler support brackets on the Northern Line vehicles (95TS). Strain gauge testing was due to take place on the brackets and the opportunity was taken to fit a gauge at the crack initiation point for crack type A. This resulted in a fatigue life estimate of 11 years with a 2.3% probability of crack initiation, according to the fatigue analysis methodology provided in BS 8118 "Structural use of Aluminium"

The original delivery of the 96TS was in a six-car formation similar to the 95TS. While there are a number of differences between the stocks the theoretical maximum force at the UNDM / Trailer position was similar; 95TS (15.47kN) and 96TS (13.3kN). It therefore is considered reasonable to assume the fatigue life of a 96TS six car formation fatigue life under a 2019 duty would be of a similar magnitude to that measured on the 95TS and would be well below the original 36-year minimum requirement.

Further details of the assessment of the fatigue life of the carbody structure can be found in [Ref 2]

13. Coupler Release mechanism

The 96TS coupler drawgear has a feature to release the compressive loadpath from the coupler in the event of a collision above 3 km/hr or 311kN (nominal force) to allow the anticlimbers to engage and absorb collision energy. Above 10km/hr the carbody structure is designed to collapse in a controlled manner absorbing the collision energy. This release feature should only ever occur under a collision event, however from reviewing the available documentation the coupler drawgear have been partially or fully releasing in service since shortly after stock introduction. These tend to be identified by customers who pull the passenger emergency alarm or report as unusual noise.

The release mechanism is comprised of spring-loaded jaws in the crossbeam which is designed under sufficient compression of the rubber springs during an impact to ride up a collar on the tie-bar assembly forcing the jaws open and disengaging the release tube from the crossbeam assembly. However, under normal service forces the jaws can creep open until one or both sides release.

When a coupler releases in service this allows the car anticlimbers to contact under braking in an uncontrolled manner and increased impact loading through the coupler assembly to the carbody structure under acceleration. Under partial release (one side only) the intercar loads are transferred through one support bracket only (doubling the load) but also resulting in a moment within the drawgear assembly which it is not designed for.

Initially when this occurred the coupler assemblies were removed and sent for warranty spares. A mitigation was put in place in 2002 to inspect the jaws on exam (14 calendar days) and return to the OEM for resetting, in 2004 a special tool was developed to allow resetting of the drawgear jaws within the depot.

Following the introduction of the L17 cars, 5 drawgears (on SpT to UNDM position) released in service over a 5-month period which prompted an investigation by Alstom - report Jubilee Line L17 Drawgear Investigation Report (L17-ESD-5668) (Issued December 2007)

The report concludes:

> *"The performance of each type"* (L14, L17) *"is effectively the same. But it is concluded that the original design has a characteristic that increases the risk of drawgear tripping. It appears that this risk – due to the use of rubber springs in the drawgear assembly that have not been stress relieved – diminishes with prolonged service operation due to the material characteristics of the springs."*

It also states that with the current mitigation in place, estimates were that approximately one L17 drawgear per year might be expected to trip and *"once the fault is detected and the train driver* *alerted, the train is withdrawn from service immediately, The failure is not safety critical. The train can be moved as normal despite the tripped drawgear."*

The report recommends that the drawgear are monitored, springs are scragged in future and the design reviewed with a view of making an improvement on the next overhaul.

It is also clear from the report that several static and dynamic load tests were completed in 2007, of these there were a number where the drawgear failed to collapse as was intended. There appears to have been a difference of opinion between Voith and Alstom over the validity of these tests.

In line with the recommendation prior to the next overhaul options for improvements were being reviewed. It is clear from a letter from Voith dated 13.2.2009 that they were proposing a complete replacement of the overload release system and had low confidence in the current design to always perform as required in a collision scenario.

> *"The system is insufficient for everyday use as we know that the overload release tends to open in an uncontrolled way. This leads to the need for fortnightly inspections and 'routine resets.' When subjected to heavy impacts such as those caused by an accident, the system is fully ineffective as its components rather tend to collapse than initiate the opening mechanism. This has been sufficiently proven in all of the tests that were conducted jointly by Voith and Alstom in Gorlitz and Braunschweig." "In our opinion modifications to the jaws and tube would not solve the problem"* - Voith Turbo Scharfenberg GmbH & Co. KG

The coupler assemblies were overhauled by Glentworth in 2012 which also included a design modification to eliminate the unintentional release events in service. A two car (4 week) trial (SpT / UDUM position) was completed. The post trial inspection identified the jaws had moved on one drawgear assembly, so an additional bush was added to the modification which Glentworth were confident would eliminate further jaw creep. The investigation was not able to identify any evidence that there was retrial with the new bush or if a static load test with the new arrangement was completed to demonstrate correct operation under the proof loads prior to implementation.

A review of recent fleet work orders relating to coupler release was made as part of the investigation into longitude cracks which identified that there was a total of 61 work orders for jaw resets or for the drawgear to be replaced (at least 7) between January 2019 and December 2019 and were distributed across the coupler positions, Figure 14. At this time drawbar release was known as "latching" and was considered a routine activity with low concern linked to the number of resets or replacements.

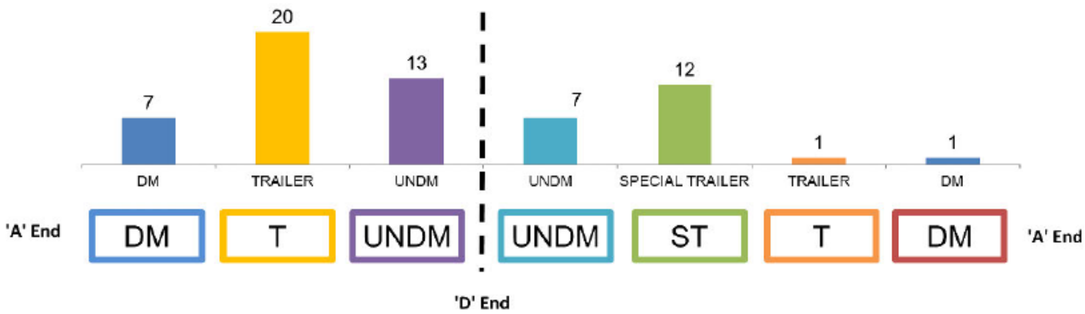

Figure 14: Locations of coupler jaw opening and reset and release and replace (Jan – Dec 19)

Due to the concerns around increased forces on the carbody as a result of coupler release and the possible effect on longitude crack growth CCSO 397 was put in place with the aim to eliminate coupler release in service. This was done by tightening up the process around inspection and reducing the allowable jaw opening width from 10mm (historical inspection) to 6mm, then reduced further to 4mm due to in-service failure. Between December 2019 and April 2020, a total of 24 resets / replacements were required. Of these there was one full release resulting in contact between anti-climbers in service and one partial release which could not be reset within the depot.

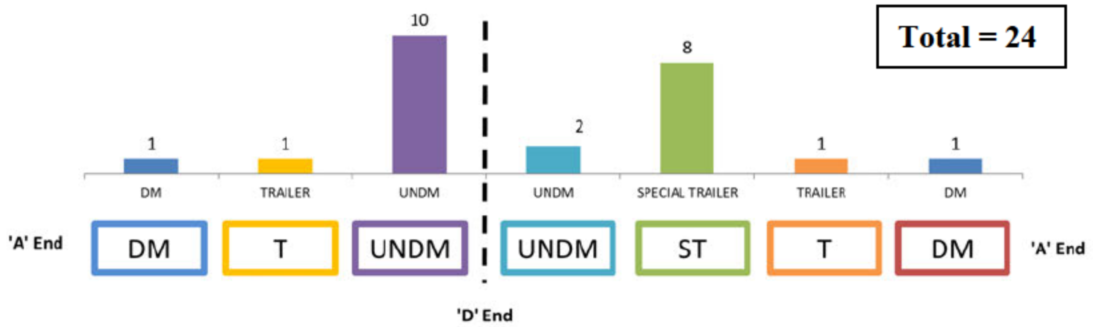

Figure 15: Locations of coupler jaw opening and rest and release and replace (Dec 19 – April 20)

It should be noted that within all the associated documents relating to the inadvertent release of the coupler there is no reference or recognition that this would increase the loading through the drawgear assemblies into the carbody structure, or that a single-side operation would occur prior to full release of the coupler.

Further details of the design, history and investigations regarding coupler failure modes can be round in [Ref 7]

14. Ampep Bearing

The Ampep bearing fitted to couplers and drawbars which allows rotation and transfers the forces to the drawgear have been a known failure mode for may years. A review of the distribution of failures compared to fatigue cracks does not support a causal link. The bearing fibreslip coating is lost causing metal on metal wear typically 5 years + post overhaul, which is not dissimilar to those fitted to the Central Line trains which also have a short life even though the coupler loads are significantly lower than those seen on the Jubilee Line. Worn ampep bearings if not replaced could result in impact loading within the drawgear increasing the forces seen by the carbody structure that will negatively affect the longitudes' fatigue life. The current Ampep bearings are not considered fit for purpose and are being changed to a new design at the next overhaul

Further details of the ampep bearing failures can be found in [Ref 6]

15. Conclusions

1. The 500kN tensile autocoupler requirement was applied to the equipment but not the structure it was attached to and there was no assessment of the fatigue requirements due to the in-service coupler forces indicating that the focus was to pass specification requirements rather than demonstrate fitness for purpose of the designs.
2. The introduction of the seventh car has the largest negative impact on the fatigue life of the longitude at the intermediate ends, most significantly at the UNDM to special trailer position and is the reason why the Jubilee Line has a widespread crack issue and the Northern Line does not.
3. The 96TS FEA was unconservative in the way it applied the coupler proof loadcases into the carbody structure which resulted in an incorrect understanding of the distribution of stress within the inner longitude.
4. The two areas of increased stress identified within the FEA as a result of the coupler compressive proof loadcase were inadequately investigated. The areas of increased stress around the "dummy bracket" were not considered further even though significant assumptions had been made and the body shell test report failed to make reference to the weld HAZ with a reserve of 0.77 due to the 400kN compressive coupler proof requirement.
5. Due to the test failure of the Radenton coupler support brackets several modifications were required for it to meet the proof requirement, the implications of these changes and the design in general were not fully considered with respect to its impact on the carbody structure.
6. The carbody structural design at the interface with the coupler support bracket has not considered either the implications of this area being a critical clamped load path, or the difficulty in maintaining a flat interface due to the likely deformation and build up of residual stresses when fabricating the assembly.
7. The failure to maintain a flat interface at the headstock / longitude weld will result in bending of the longitude flange and redistribution of the stress to the inner radii and rear fixing holes further reducing the fatigue life at these critical locations.
8. There has been a clear misconception that the carbody structure was designed to meet the in-service requirements of seven car operation in ATO while in fact it was designed to meet the seven car crashworthiness requirements. This fact was identified within the L19 project however the correct analysis was not completed.
9. The change in the rate of acceleration introduced at the same time as ATO rather than specifically the ATO functionality itself resulted in a further reduction of fatigue life at the carbody longitude, however this is considered to have a much lower impact than the additional seventh car.
10. The fatigue life of the inner longitudes at the special trailer to UNDM position is in the region of 2.25 years (2.3% probability of crack initiation) at 2019 service duty.
11. The predicted fatigue life of the inner longitude at the intermediate ends with the highest coupler forces is very unlikely to meet the minimum 36-year requirement in the six-car formation with or without the introduction of ATO / TBTC.

12. The fatigue life of the Northern Line 95TS carbody inner longitude was measured at 11 years. It is therefore considered possible that cracks have started to initiate at some UNDM / Trailer positions and cracks may currently (or in the near future) be identifiable by NDT.

13. The proof requirement for the carbody inner longitude was not met at the intermediate end positions at the longitude to tertiary headstock connection due to yielding at the weld HAZ.

14. The coupler release mechanism on the 96TS has suffered significant numbers of failures since stock introduction which result in increased stress within the drawgear and carbody structure as well as car to car impact in service. This is not considered to be an acceptable position going forward and CCSO 397 has been generated to control the risk until the failure mode is eliminated

15. It is considered unlikely that the coupler release mechanism will correctly operate to remove the loadpath from the coupler in the event of a collision at all coupler positions.

16. The measured forces transferred by the 96TS auto-coupler and drawbar are higher than recently measured on other LU stocks, this has the potential to reduce the coupler components fatigue lives.

17. The Ampep bearing failures are not considered to be a causal factor of the longitude cracks but would also be negatively affected by the high loadings seen on the 96TS fleet. Damaged bearings should however be removed from service when identified to minimise the impact loadings into the carbody structure.

16. References

Ref 1: AOS-E-RS-Int-J067-TR_16-No-1002-A1: 96TS Underframe Structural Analysis Review

Ref 2: AOS-E-RS-Int-J067-TR_16-No-1003-A1: 96TS Underframe Structural Performance Analysis

Ref 3: AOS-E-RS-Int-I040-TR_16-No-934-A2: 96TS Longitude Failure – Original Design Report

Ref 4: AOS-E-RS-Int-1040-TR_16-No-928-A1: 96TS Train Manufacture Report

Ref 5: AOS-E-RS-Int-1040-TR_16-No-933-A2: 96TS Inner Longitude – Crack Data Analysis Report

Ref 6: AOS-E-RS-Int-1040-TR_16-No-930-A2: 96TS Longitude Failure -Ampep Bearing Report

Ref 7: AOS-E-RS-Int-I040-TR_16-No-935-A1: 96TS Longitude Failure – Drawgear Release Mechanism

Ref 8: JLE Contract 201 Rolling Stock (EMU) Particular Specification– (Nov 1993)

Ref 9: 201-021- 001 to 0009: 201 – EMD-ROS-SU-0142 Contractors Submission “Coupler” 11/06/99

Ref 10: T133 - Bodyshell strain gauge test issue 1. – (11/08/95)

Ref 11: F 37/1 Bodyshell FEA Intermediate / Trailing End (16/08/94)

Ref 12: Final Design Submission for Bodyshell L17/TR/009 issue 2 24/06/2004

Ref 13: Report L14/ESD/06270 – Study into the effects of implementation of TBTC on car body Stress (Issue 2)

Ref 14: 201/C/01/BA/008 rev L: Headstock arrgt trailing end sheet 2 (15/3/94)