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Light Rail Safety Investigation Report

Fractures of Urbos 3 LRV underframes — Sydney Inner West Light Rail Line, 27 October 2021

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Sydney Inner West Light Rail Line

27 October 2021

Cover image: OTSI

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Contents

Table of figures

List of tables

Executive summary

In late September 2021, fractures were identified in the underframe of Sydney Urbos 3 light rail vehicles (LRV) operating on the Inner West Light Rail (IWLR) line. The fractures were identified by maintenance staff in the underframe rotation bump stop (RBS) during a routine maintenance inspection. The fractures had not resulted in a rail safety incident such as an LRV derailment.

Following the discovery of the fractures in late September 2021, additional inspections of the LRV's bogie box area were carried out in response to a Construcciones y Auxiliar de Ferrocarriles (CAF) recommendation. Inspection of that area required each of the 12 LRV units to be removed from service for several days. The additional inspections identified multiple fractures on all LRV C modules within the underframe bogie box area, with the presence of those fractures representing a derailment risk. Sydney Urbos 3 services were subsequently suspended in late October 2021 (the *incident*).

The Urbos 3 LRVs were designed and manufactured by CAF in 2013. Prior to the discovery of the fractures in the Sydney LRVs, Urbos 3 LRVs in use overseas had experienced similar fractures in the same area. Those fractures were identified around 22 months earlier in the Urbos 3 fleet operating in Birmingham, United Kingdom.[1] CAF advised Transport for NSW (TfNSW) as the asset owner, of the Birmingham LRV fractures about 3 months prior to their discovery in the Sydney LRV fleet. The advice was also communicated to ALTRAC (the organisation responsible for maintaining the Sydney LRVs) and ALTRAC's contract partners Transdev and Alstom. TfNSW, ALTRAC, Transdev and Alstom subsequently engaged with CAF regarding the fractures. CAF advised that it was not necessary to carry out specific or additional inspections as long as the vehicles were being operated and maintained as per their design. As of September 2021, the LRVs had travelled approximately 19 per cent of the total distance they were expected to travel in their 30-year design life.

The Office of Transport Safety Investigations (OTSI) commenced an investigation into the Urbos 3 underframe fractures on 3 November 2021. OTSI's investigation initially focused on the timeline of the underframe fracture detection and eventual suspension of the IWLR fleet. It then reviewed the safety aspects of the Urbos 3 procurement – sourcing, design, build and commissioning – and operation and maintenance arrangements relevant to the risk of underframe fractures. The OTSI investigation also reviewed the results of CAF, ALTRAC (including Transdev and Alstom) and TfNSW's technical investigations. Those investigations offered insights into how the fractures were considered to have occurred. While the technical investigations differed as to where and how the fractures first commenced, OTSI identified safety lessons from the investigations, resulting in recommendations made to the applicable organisations. Based on an analysis of the available evidence, OTSI identified a number of factors considered to have contributed to the incident, and other factors considered to have increased the risk of Urbos 3 operations on the IWLR line.

[1] The Birmingham Urbos 3 fleet had a relevantly similar design to the Sydney Urbos 3 fleet but were not identical. The Birmingham Urbos 3 design included a similar bogie, bogie box structural configuration and locations where fractures were identified in the underframe.

Full details of the findings and recommendations of this light rail safety investigation are contained in Parts 3 and 4 respectively.

Those factors considered to have contributed to the incident included:

a. The 2013 Urbos 3 design (original Sydney design reviewed and accepted by the asset owner) was not sufficient to meet in-service operational loading, with fatigue mode fractures[2] developing in the underframe as a result.
b. The maintenance regime[3] was not sufficient to detect the presence of fractures in the underframe rotation bump stop (RBS) and L bracket locations that were likely in place for months prior to the incident.
c. Proactive inspections of the underframe locations were not initiated by those organisations involved in the maintenance regime in a timely manner. That was despite there being knowledge of similar fractures identified in overseas Urbos 3 vehicles and considering the risk of LRV derailment due to a fractured underframe.

Following are summaries of recommendations made to the relevant responsible entities.

Asset owner, TfNSW:

i. Review of its LRV procurement process to consider; supply of light rail track maintenance standards and actual measured track geometry data, additional design reporting requirements and commissioning tests to support validating LRVs to meet their specified design life.
ii. Review and approve updates of the Sydney IWLR Urbos 3 technical maintenance plan (TMP) from a technically competent organisation to cover; improvements in RBS clearance management, modified underframe inspections following post incident underframe repairs and any additional areas of inspection derived from TfNSW's underframe structural analysis.
iii. Review of its Safety Management System (SMS) to assess the need for guidance on directing its asset maintainers to undertake proactive investigations of reported original equipment manufacturer (OEM) component failures.
iv. Review its light rail track geometry standard to ensure it is fit for purpose to manage passenger safety requirements consistent with the relevant light rail vehicle ride comfort for passengers - measurement and evaluation standard.

Urbos 3 designer, CAF:

v. Review of its finite element analysis (FEA) design process to assist in validating fatigue design life assessments achieve compliance with their required design life.
vi. Review of its welding quality assurance process to consider including a review of critical structural welds that would not be accessible to examine once full assembly of the welded structure is complete.
vii. Review of its commissioning process to consider the need for recording any additional bogie configuration shimming configurations.
viii. Update the Urbos 3 TMP procedures to improve clarity on RBS clearance management and modified underframe inspections following post incident underframe repairs.

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[2] A fatigue mode fracture in metal occurs due to cyclic loading with a lower loading than that necessary to cause fracture in a single loading application.

[3] The maintenance regime included a number of organisations, each playing their respective roles. The organisations included; CAF (designer of the Urbos 3, author of the technical maintenance plan (TMP) inclusive of maintenance instructions and also a source of Urbos 3 technical advice to its customers), TfNSW (Urbos 3 asset owner and reviewer/approver of changes to the Sydney Urbos 3 TMP), ALTRAC, Transdev and Alstom (organisations involved in the operation and maintenance of the Sydney Urbos 3 LRVs in accordance with the TMP). See paragraph 1.10 on page 10 for further details.

ix. Review of its SMS to assess the need for guidance on when to direct its clients to undertake proactive inspections of reported LRV component failures.

Accredited Urbos 3 operator and maintainer, ALTRAC:

x. Undertake audit activities to provide assurance that the Urbos 3 training and competency assessment system adequately meets its SMS expectations.

xi. Review of its SMS to assess the need for guidance on directing its contracted maintainer to undertake proactive investigations of reported OEM LRV component failures.

Contracted Urbos 3 maintainer, Alstom:

xii. Continue to progress and finalise improvements in the Urbos 3 training and competency assessment system for Urbos 3 maintenance staff.

xiii. Consider the introduction of a program to rotate technical staff across vehicles to provide an opportunity for staff to work on different vehicle types.

Part 1 — Factual information

Events leading up to the occurrence

1.1 In late 2019, fractures were identified in the West Midlands Metro (Birmingham, United Kingdom) Urbos 3 Light Rail Vehicles (LRV) in the underframe rotation bump stop (RBS) brackets[4] and underframe bogie box area.[5]

1.2 In February 2020, the Urbos 3 LRV manufacturer Construcciones y Auxiliar de Ferrocarriles (CAF), determined the root cause of underframe fractures in the Urbos 3 Birmingham fleet was due to bogie RBS contact loading with the underframe RBS.

1.3 During May 2020, and June 2020 CAF undertook temporary repairs to the Birmingham Urbos 3 LRVs in the bogie box structure.

1.4 On 11 June 2021, the Birmingham Urbos 3 LRVs were suspended from service following the discovery of additional fractures in the bogie box area, including in vehicles that had undergone temporary repairs. Information regarding the detection of these factures was provided a few days later to Transport for NSW (TfNSW) as the asset owner and ALTRAC, Transdev and Alstom, the organisations responsible for Urbos 3 maintenance. The information provided by CAF reported the fracture root cause had been analysed with the cause not affecting the Sydney Urbos 3 fleet as long as the infrastructure, operational and maintenance aspects remained as considered during the vehicle's design phase.

1.5 On 27 September 2021, fractures in the Sydney Inner West Light Rail (IWLR) Urbos 3 LRV underframe RBSs were detected during a routine maintenance inspection carried out by Alstom at the Lilyfield Urbos 3 maintenance depot. The maintenance technician who detected the fractures was transferred to the depot two weeks prior to assist with undertaking inspections because of a COVID outbreak at the depot.

1.6 Three weeks later, a recommendation was made by CAF to TfNSW to carry out a targeted inspection of the Urbos 3 fleet in the bogie box area.

The occurrence

1.7 Results of the targeted bogie box area inspections identified a range of fractures underneath the seating in the bogie box area and in the underframe RBS.

1.8 On 27 October 2021, operation of the Sydney IWLR Urbos 3 LRV fleet was suspended due to the fractures.

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[4] The underframe rotation bump stop (RBS) was a metal structure welded to the underframe that consisted of a vertical contact pad. An RBS would limit the turning rotation of an LRV bogie operating through curved track.

[5] The bogie box area of an Urbos 3 LRV was a section of the underframe where the LRV bogie was connected to the LRV carbody and where the weight of the carbody acted on the bogie.

LRV operations

1.9 The Sydney IWLR line (L1) operated between Central Station and the Dulwich Hill Interchange, over 12.8 km with 23 stops (Figure 1).

Figure 1: Inner West Light Rail Line

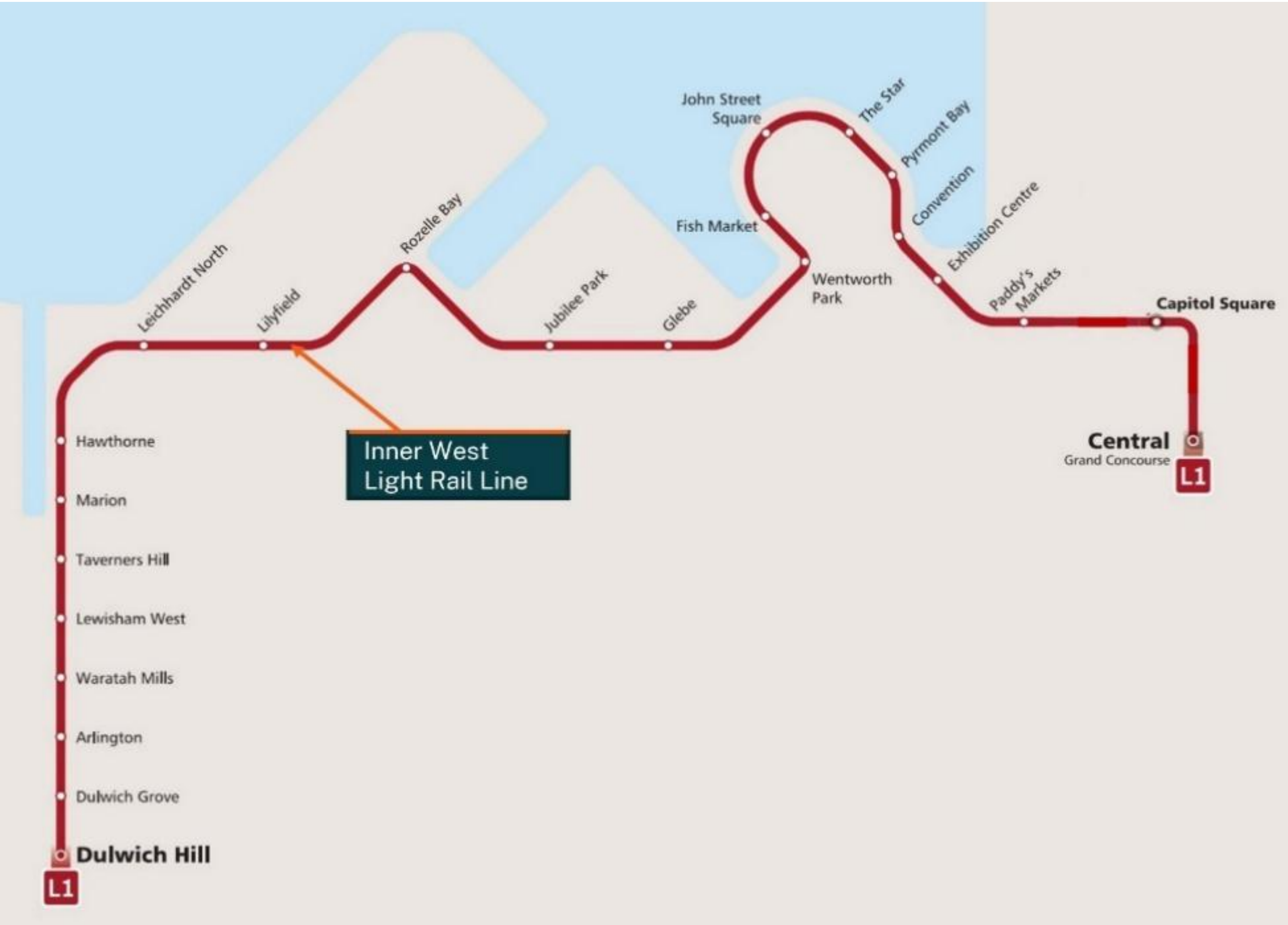


Image depicting the IWLR line (L1) between Central Station and Dulwich Hill.
Source: Transport for NSW, modified and annotated by OTSI

1.10 Several organisations played a role in the Sydney IWLR Urbos 3; design, manufacture, maintenance regime and its operation at different points in time. They included:

a. CAF – the designer and manufacturer of the Sydney Urbos 3 LRVs that were first delivered in December 2013. CAF also supplied the Urbos 3 original Technical Maintenance Plan (TMP), spare parts and limited technical support upon request to Alstom from July 2015 as part of the maintenance regime. CAF obtained the status of an Authorised Engineering Organisation (AEO)[6] from TfNSW for the design and manufacture of LRVs on 30 July 2015.

[6] An Authorised Engineering Organisation (AEO) status was received by an organization from TfNSW having satisfied TfNSW that it could construct and maintain TfNSW assets such as an LRV.

b. CAF Rail Australia Pty Ltd (CAF Australia) – the initial maintainer of the Urbos 3 LRVs following their delivery in December 2013. CAF Australia maintained the Urbos 3 LRV fleet until the end of June 2015.[7]

c. TfNSW – the IWLR rolling stock and infrastructure asset owner who accepted the Urbos 3 LRVs for operation following their commissioning from July 2014. TfNSW also managed the review and approval of the TMP maintenance standards and had in place a contract with ALTRAC since December 2014 to operate and maintain the Urbos 3 LRVs.

d. ALTRAC Light Rail Partnership (ALTRAC) – the accredited light rail operator from August 2018. ALTRAC had in place arrangements with the following organisations to provide the operation and maintenance of Urbos 3 LRVs on the IWLR line.

    i. Transdev Sydney Pty Ltd (Transdev [ALTRAC's subcontractor]) – the Urbos 3 operator that employed all LRV operational staff which included drivers and light rail control staff. Transdev held accreditation for the Urbos 3 operation from July 2014 until August 2018. Transdev was contracted by ALTRAC for the operation and maintenance of the Urbos 3 on the IWLR line. Transdev subcontracted the Urbos 3 maintenance to Alstom.

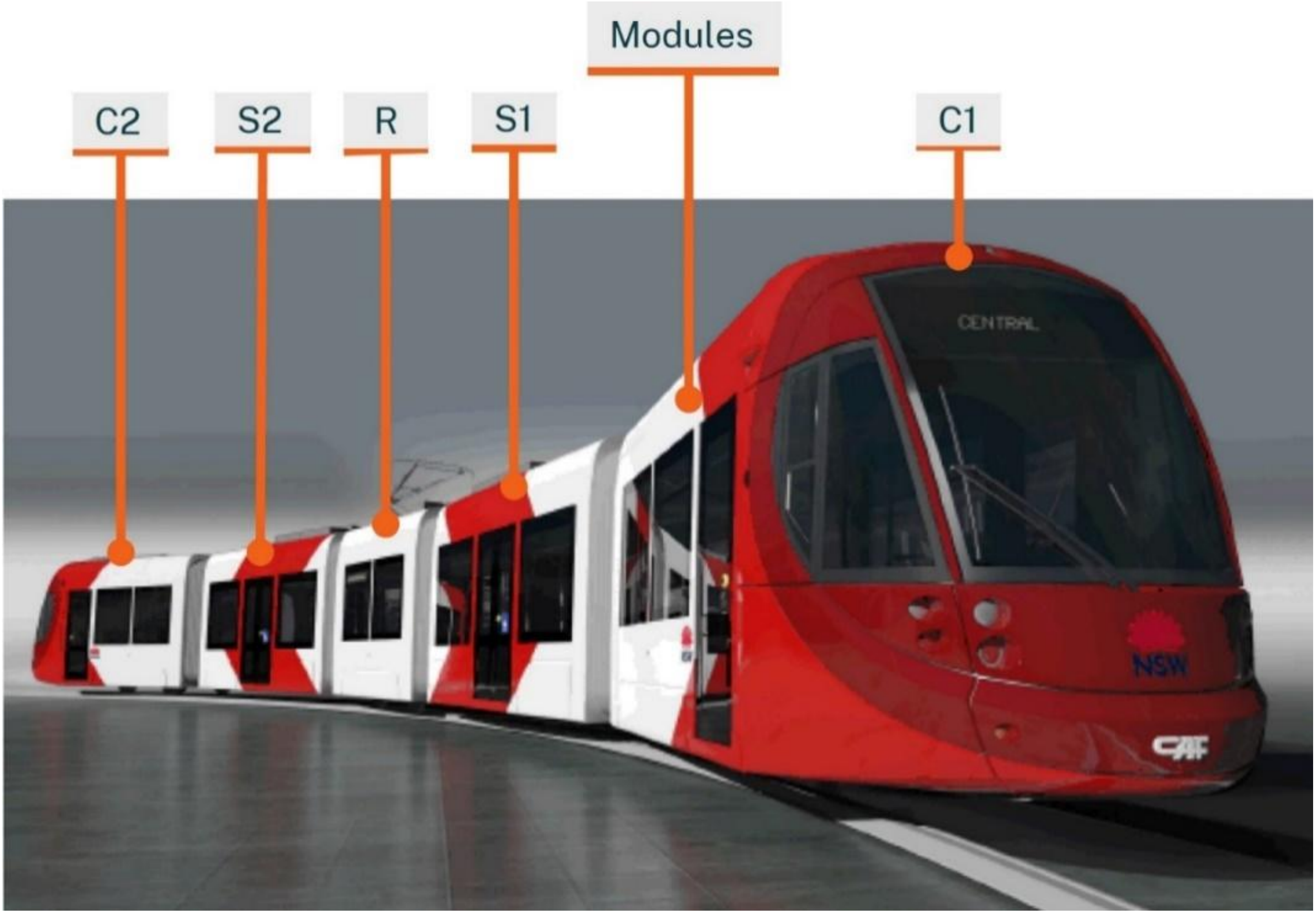
    ii. Alstom Transport Australia Pty Ltd (Alstom) [Transdev's subcontractor]) – the Urbos 3 maintainer that was responsible for the maintenance of all infrastructure assets in accordance with the TMPs from July 2015. The infrastructure included Urbos 3 LRVs, track, signalling and train control assets.

LRV information

1.11 The Urbos 3 LRVs operated on the IWLR line were designed and manufactured by CAF in Spain. The LRV units were configured with 2 lead modules (C modules) and 3 trailing modules (S and R modules) (Figure 2).

[7] CAF Australia commenced maintenance of the Variotrams and Urbos 2 LRV fleet from November 2012 under contract to TfNSW. Prior to November 2012 Variotrams operated on the IWLR line from 1997 and were maintained during that period by their manufacturer Bombardier.

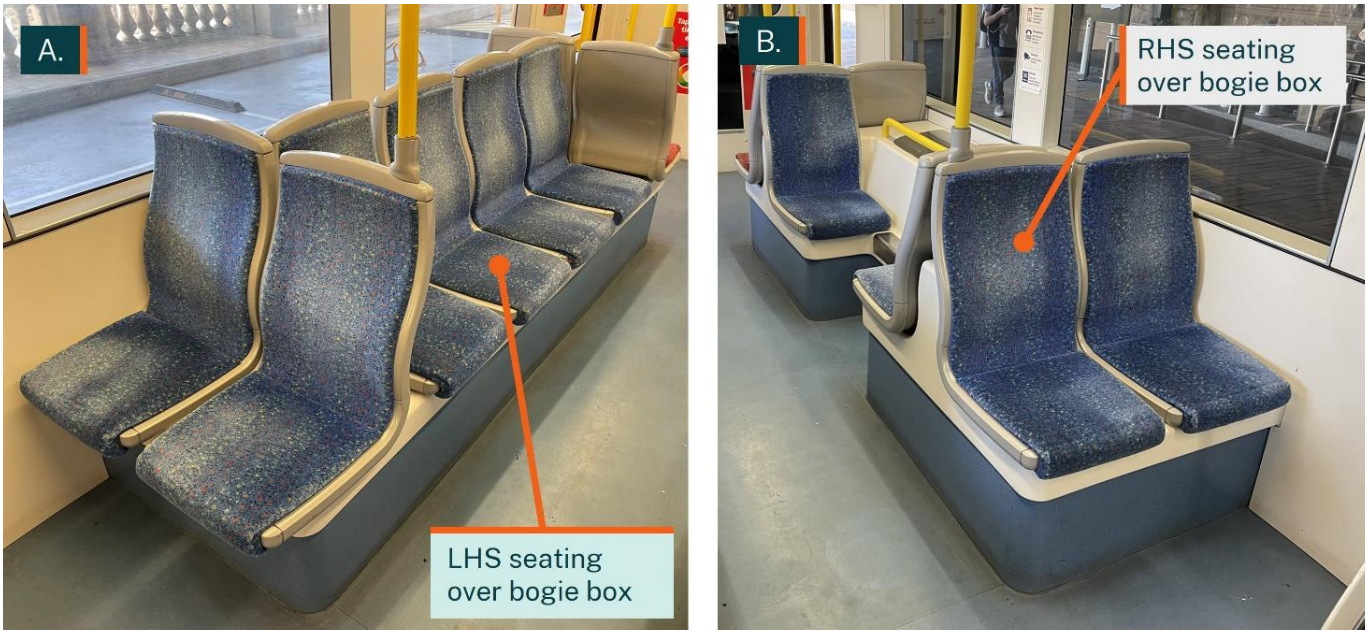
Figure 2: Urbos 3 LRV unit



Graphic design impression of a Urbos 3 LRV unit with 5 modules identified as C1, S1, R, S2 and C2.
Source: CAF, annotated by OTSI

1.12 The underframe fractures which led to LRV services being suspended were found on the C module bogie boxes under the passenger seating arrangements (Figure 3).

Figure 3: Urbos 3 C module carbody seating arrangements over bogie box



Urbos 3 C module carbody seating arrangements. Image A: left-hand side (LHS) seating over LHS bogie box. Image B: right-hand side (RHS) seating over RHS bogie box. Fractures were identified in both LHS and RHS bogie box locations following removal of the seating. Source: OTSI

Fracture locations

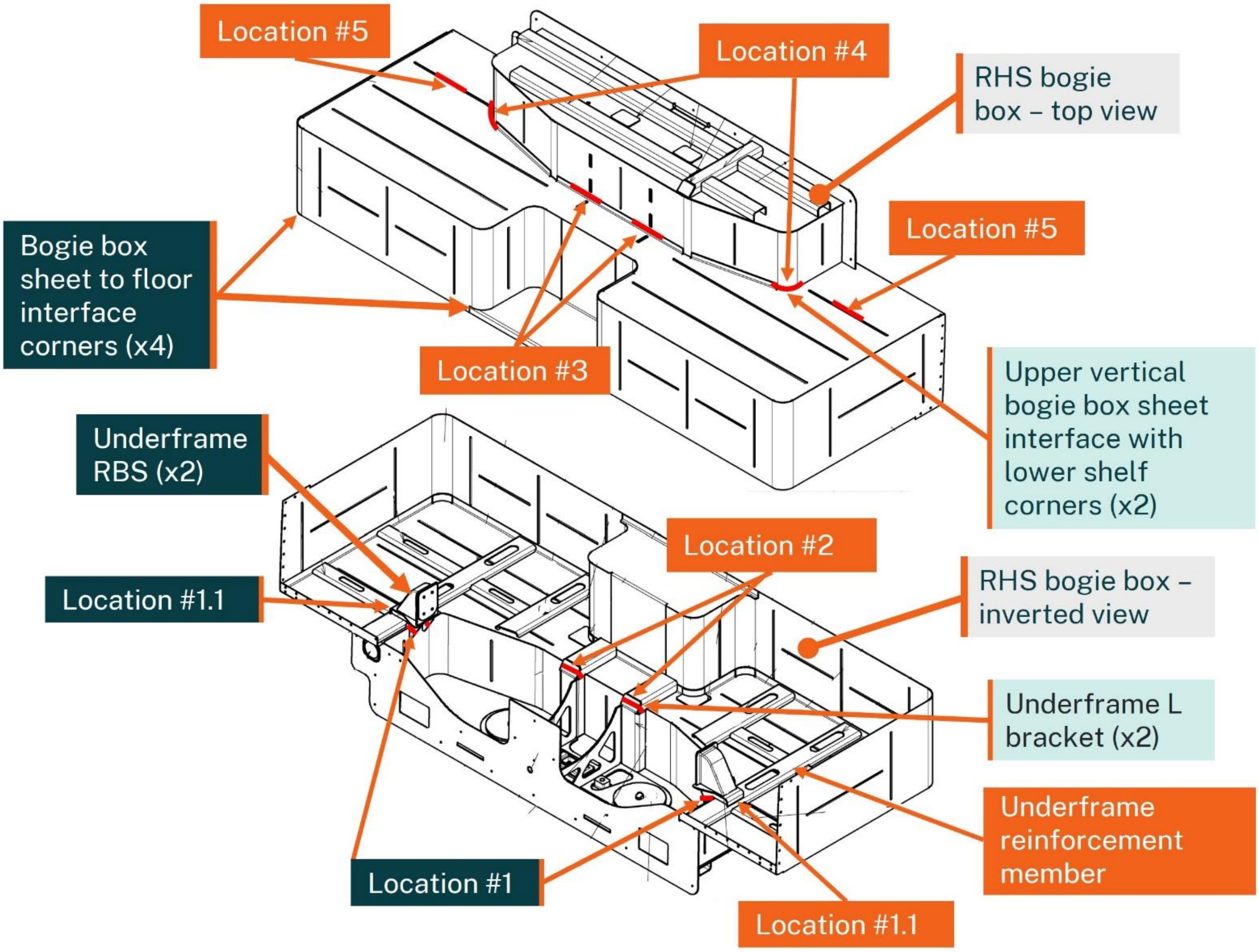
1.13 Underframe fractures were found in 5 common areas on the C module through visual and non-destructive inspections[8] (Figure 4).

1.14 As shown in Figure 4, the location of fracture location #1 in the underframe RBS was close to facture location #4 in the top side bogie box sheeting. In addition, fracture location #2 in the L bracket[9] structure was adjacent the top side bogie box sheeting at fracture location #3.

[8] Non-destructive testing (NDT) included dye penetrant testing where surface-breaking defects were identified using a pink liquid dye.

[9] An L bracket was an L shaped fabricated channel section welded into the bogie box structure. Details of the L bracket are depicted in Figure 14 on page 29.

Figure 4: Underframe right-hand side bogie box fracture locations

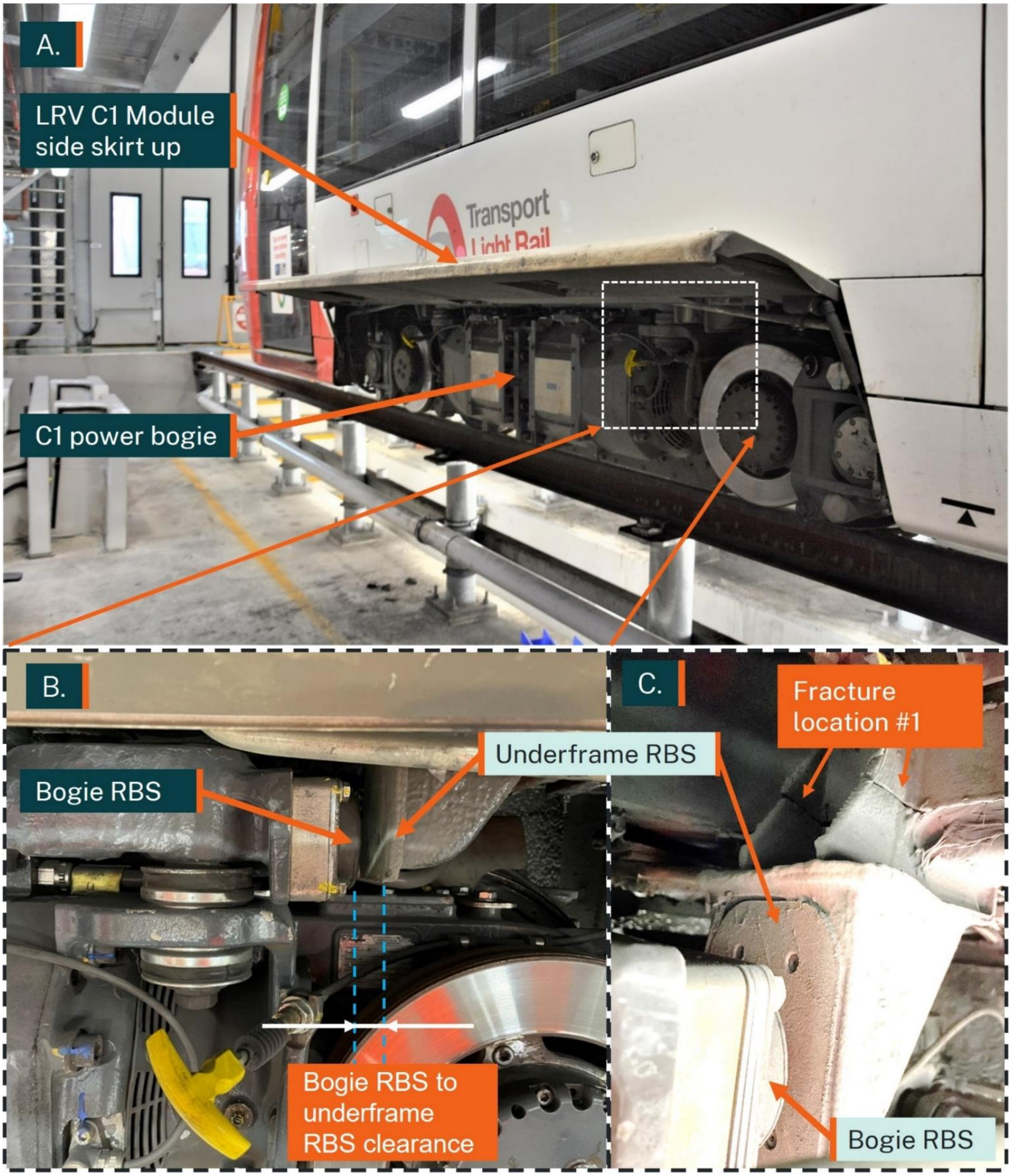


Top and inverted view of the RHS underframe bogie box assembly depicting typical fracture locations of both RHS and LHS bogie boxes identified during visual and non-destructive testing. Fractures underneath the bogie box structure of the underframe were identified at Location #1 in the underframe RBS gusset, and Location #2 in the L bracket corner. Fractures on the top side of the bogie box structure were identified at; Location #3 in the bogie box sheeting interface between the upper vertical sheet and lower shelf, Location #4 in the upper vertical bogie box sheet with lower shelf corners, and Location #5 along the lower bogie box shelf sheeting. No fractures were identified in the horizontal welding of the RBS structure to the underframe reinforcement members at Location #1.1. Location #1.1 provided a reference location for the TfNSW design assessment review.
Source: CAF, TfNSW, annotated by OTSI

Underframe rotation bump stop – Fracture location #1

1.15 Fractures were initially found in the LRV underframe at the RBS – Location #1 (Figure 5 and Figure 6). Fracture of the LRV underframe at the RBS location was observed to have extended into the underframe bogie box sheeting, and in some cases underframe reinforcement member (Figure 6).

Figure 5: Underframe RBS fracture location relative to LRV carbody and bogie



Underframe fracture location #1 relative to LRV carbody and bogie. Image A: LRV C1 module on an inspection road (depicting view outside of inspection pit) with side skirt raised showing C1 motor bogie. Image B: Close up view of bogie RBS and underframe RBS with clearance between the two surfaces that could have made contact when an LRV traversed a curve. Image C: Close up view of the bogie RBS, underframe RBS and fracture location #1 in both RBS triangular gussets.
Source: OTSI

Figure 6: Underside view of bogie box and underframe RBS fractures

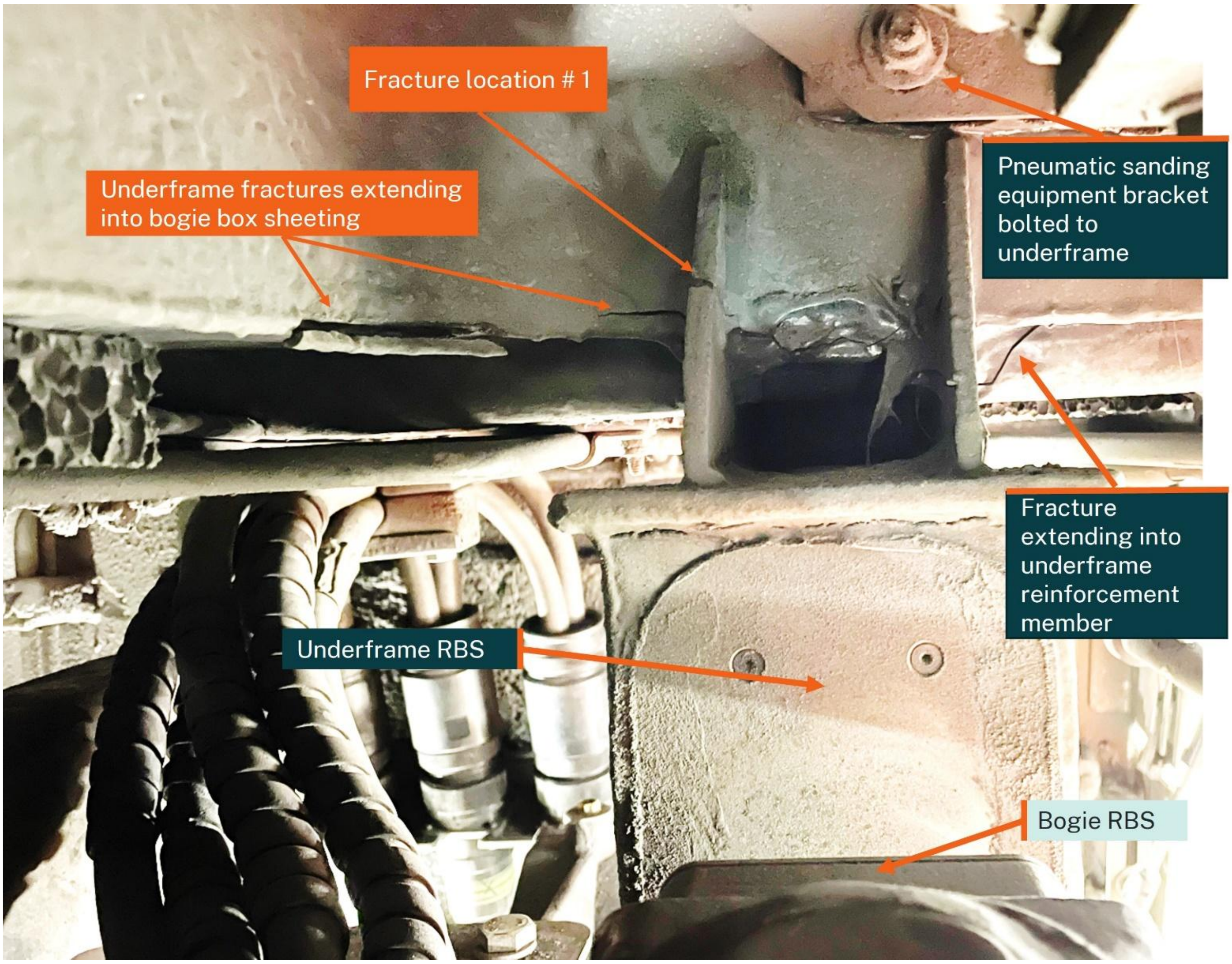
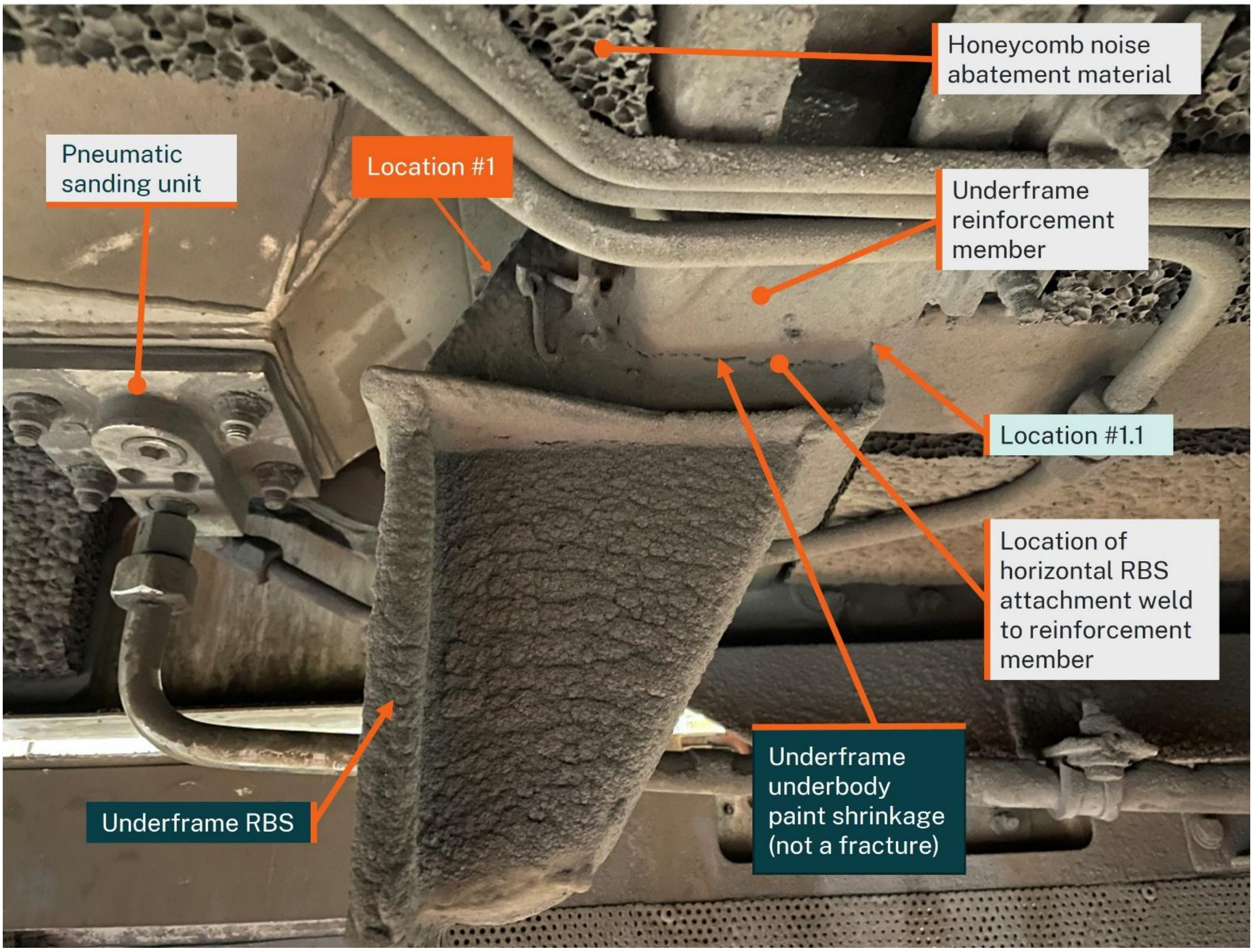


Image depicts bogie box sheeting fractures, single gusset fracture at location #1 and fracture extending into underframe reinforcement member. Image also depicts pneumatic sanding equipment bracket bolted to the underframe. Underframe RBS and bogie RBS visible in foreground. Image taken with LRV on an inspection pit, LRV side skirt raised, with view from outside of inspection pit.
Source: OTSI

1.16 The underframe RBS was welded to a reinforcement member with vertical and horizontal fillet welds. The surface of both the underframe RBS and reinforcement member were covered with thick protective layers of paint (Figure 7). Underframe underbody paint was noted on the RBS structure with paint shrinkage (appearing as fractures in the paint surface only) along the horizontal RBS attachment weld to the reinforcement member. The underframe RBS was also located near the LRV pneumatic sanding equipment that was bolted to the underframe via an attaching bracket arrangement (Figure 6 and Figure 7). Noise abatement material (honeycomb structure) was also affixed to the underframe at various locations (Figure 7).

Figure 7: Side view of underframe RBS and components

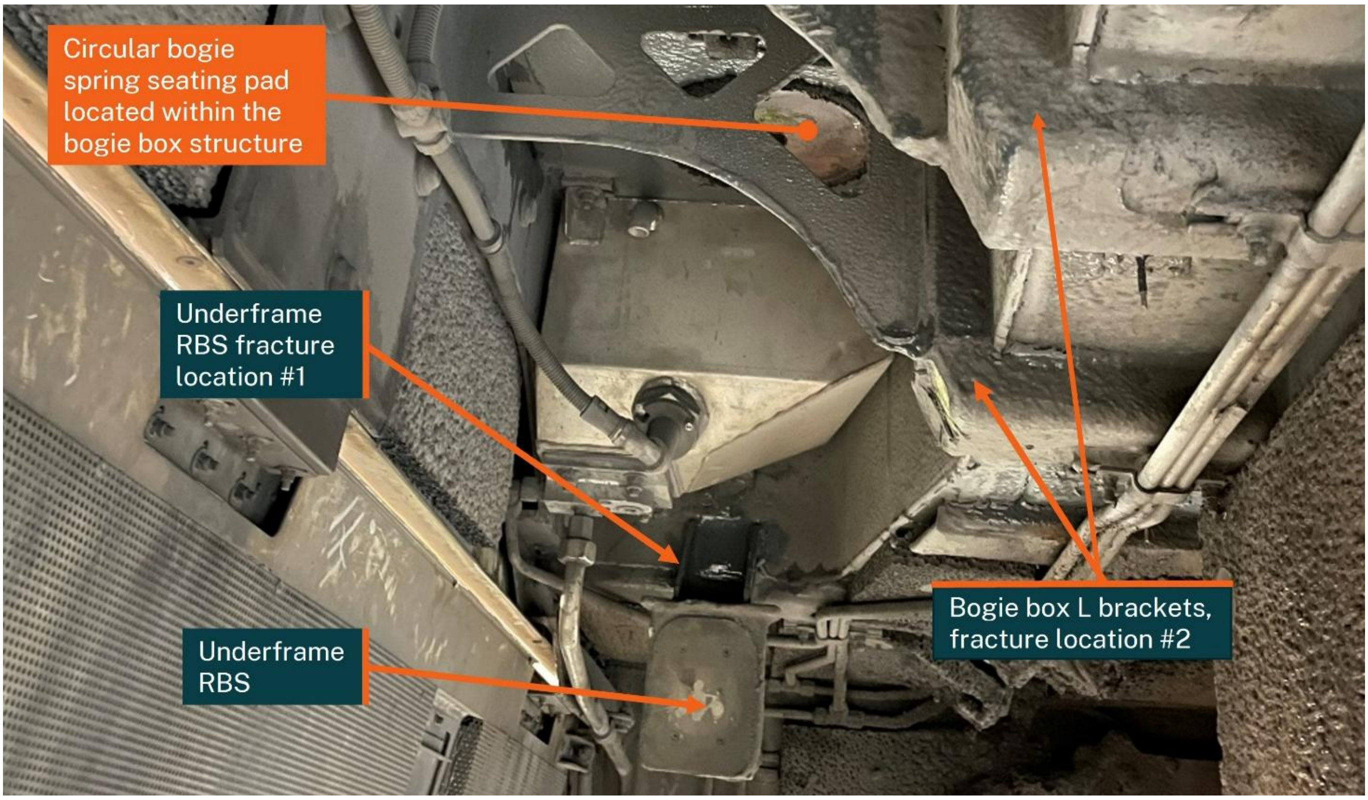


Side view of the underframe RBS facing towards the outside of the carbody with the motor bogie removed and LRV placed on lifting stands. Underframe pneumatic sanding equipment was located near the RBS structure. Underframe underbody paint was noted on the RBS structure with paint shrinkage (appearing as fractures in the paint surface only but not a fracture in the RBS) along the horizontal RBS attachment weld to the reinforcement member. Honeycomb noise abatement material was also visible covering some of the surface area of the bogie box structure.
Source: OTSI

Underframe L bracket – fracture Location #2

1.17 Fractures of the LRV underframe at the L bracket were found during non-destructive visual inspection and testing following removal of underbody paint. The underframe bogie box structure, including the L bracket location is depicted in Figure 8, with the location of an L bracket fracture depicted in Figure 9.

Figure 8: Left-side bogie box RBS fracture location #1 and L brackets fracture location #2



Left-side underframe bogie box area facing towards the C module front with the motor bogie removed and LRV placed on lifting stands. Underframe RBS fracture location #1 and bogie box L brackets fracture location #2 indicated. Circular bogie spring pad where a bogie spring seated into the bogie box frame also indicated.
Source: OTSI

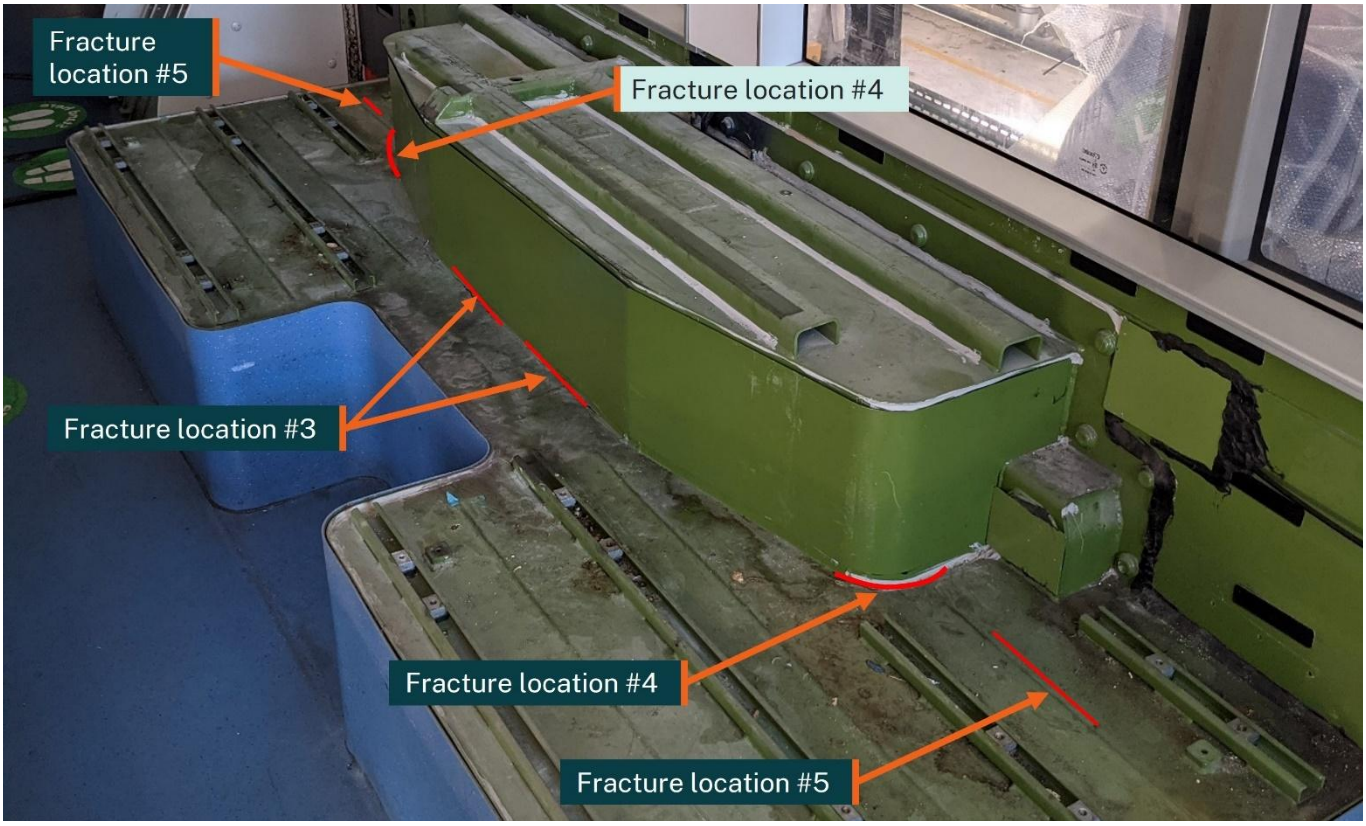
Figure 9: L bracket fracture location #2

L bracket fracture location #2 following removal of thick protective paint and application of dye penetrant testing to highlight fracture line (black line through pink dye).
Source: OTSI

Top side bogie box - fracture locations #3, #4 and #5

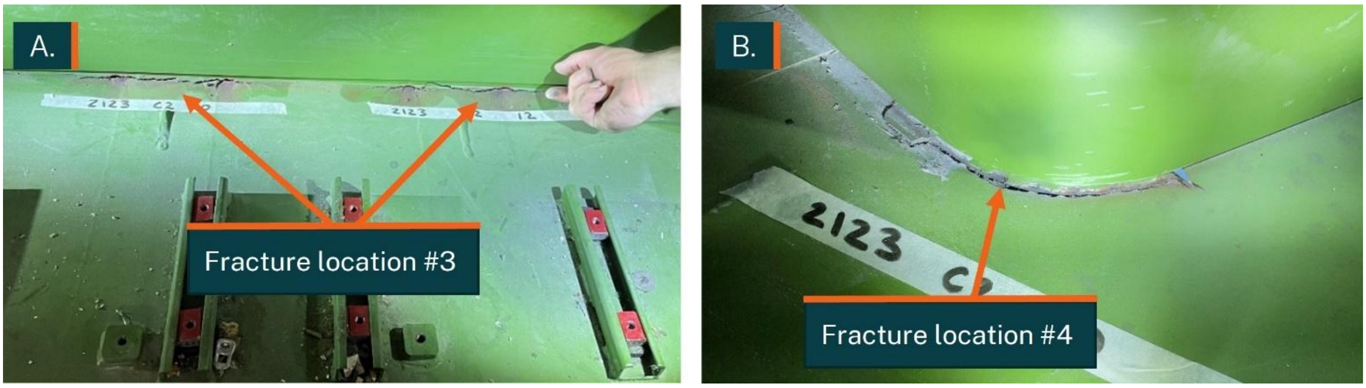
1.18 Fractures of the LRV bogie box structure were found following removal of the passenger seating and fibreglass moulding depicted in Figure 3 on page 13. The location of fractures were identified as locations #3, #4 and #5 (Figure 10) with some examples shown in Figure 11.

Figure 10: Top left hand side bogie box fracture locations #3, #4 and #5



Top side of bogie box structure (right side) with fracture locations #3, #4 and #5 identified with red lines.
Source: OTSI

Figure 11: Examples of top side bogie box fracture locations #3 and #4



Examples of top side bogie box fracture locations #3 and #4 from U2123 C2 module.
Source: OTSI

Urbos 3 Fleet fracture location data

1.19 Fracture lengths at the fracture locations were recorded, except for the underframe RBS fracture measurements. A summary of the fracture locations is detailed below and depicted in Figure 12.

a. All C module underframe bogie boxes of the LRV fleet (48 in total) were identified with fractures in the L bracket location #2 (96 L brackets).

b. Not all underframe RBS had fractures in the gussets at fracture location #1, i.e. 35 per cent of C module underframe RBS gussets were identified with fractures at location #1.

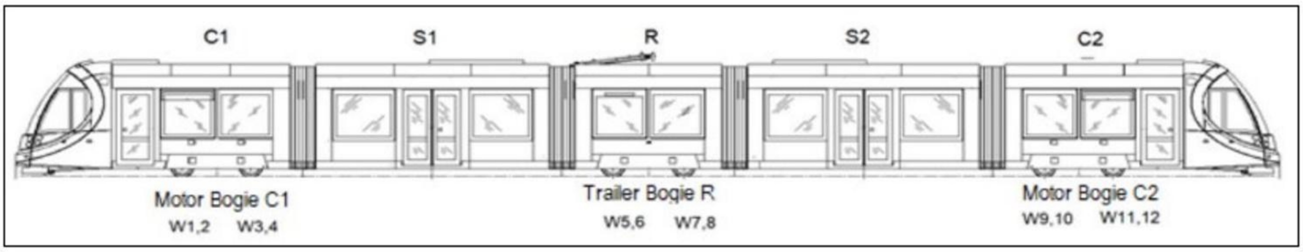
c. Some examples existed of LRV units with no underframe RBS fractures in a C module (U2112, U2116, U2118, U2121 C1 modules). However, those C modules had fractures at location #4, near the underframe RBS attachment at location #1.

d. Some examples existed of C1 modules with no underframe RBS fractures (fracture location #1) and no topside bogie box fractures at locations #3, #4 & #5 (C1 module U2112 at the RHS bogie box and C1 module U2114 at the RHS bogie box).

e. No fractures of the underframe RBS attachment to the underframe reinforcement member were detected at the horizontal and rear welds (Location #1.1).

1.20 Further details of the fracture locations and their measurements are provided in *Appendix 2: Urbos 3 fracture location data* on page 101.

Figure 12: Urbos 3 unit fracture locations, measurements and LRV kms travelled



			U2112		U2114		U2115		U2116		U2117		U2118			
		Kms	513694		503469		553961		571684		547083		560829			
C1	W1	5	0	0	0	0	0	0	0	0	40	0	80	60	5	W2
		4	80	0	130	0	100	80	340	140	140	60	70	40	4	
		3	100	0	130	0	210	0	20	80	200	150	340	240	3	C1
	W3	3	110	180	240	90	230	110	150	180	150	150	340	240	3	W4
		4	100	80	140	80	130	80	140	150	160	110	40	0	4	
		5	0	0	0	0	0	0	70	0	0	0	60	70	5	

			U2112		U2114		U2115		U2116		U2117		U2118			
C2	W9	5	0	110	50	340	0	0	60	330	0	360	100	230	5	W10
		4	150	250	100	310	80	120	120	150	130	110	50	130	4	
		3	130	210	50	150	120	260	270	340	270	310	300	350	3	C2
	W11	3	100	200	230	350	0	320	140	80	220	140	300	350	3	W12
		4	60	150	120	450	130	300	20	100	160	90	50	60	4	
		5	0	150	0	450	0	300	50	180	0	420	80	180	5	

			U2119		U2120		U2121		U2122		U2123		U2124			
		Kms	531726		531860		512744		519014		386095		512342			
C1	W1	5	0	0	40	0	0	0	250	0	0	0	40	0	5	W2
		4	120	60	80	0	100	50	200	100	120	85	110	100	4	
		3	140	55	200	100	200	90	250	100	195	200	220	210	3	C1
	W3	3	220	160	230	100	220	120	240	150	210	170	220	180	3	W4
		4	170	100	150	80	140	0	200	100	80	80	70	80	4	
		5	0	0	0	0	0	0	200	0	0	0	70	0	5	

			U2119		U2120		U2121		U2122		U2123		U2124			
C2	W9	5	0	35	30	130	210	230	60	80	0	0	30	140	5	W10
		4	165	120	110	180	90	150	120	200	70	130	120	140	4	
		3	260	315	230	240	0	60	230	320	175	250	250	400	3	C2
	W11	3	115	315	230	200	230	240	230	310	220	240	240	220	3	W12
		4	145	135	120	170	60	160	100	170	80	150	90	60	4	
		5	0	45	0	40	0	0	90	370	0	110	80	340	5	

Legend

Fracture location #1 (underframe rotation bump stop (no dimension))

Fracture location #2 (L bracket fracture)

0 | 250 | 450 — Colour gradient of fracture lengths at Locations #3, #4 & #5 in mms. The colour gradient is representative of crack length only and does not represent the structural nature or significance of each fracture location.

C1 denotes a power module C1
C2 denotes a power module C2
3 denotes fracture location #3 in bogie box
4 denotes fracture location #4 in bogie box
5 denotes fracture location #5 in bogie box
W# denotes the wheel position on an LRV bogie i.e, W1, W2, W3…….

Source: ALTRAC, CAF, OTSI tabulation

Fracture detection timeline

1.21 Globally, Urbos 3 LRVs operating in Belgrade Serbia, Besançon France, Birmingham United Kingdom and Sydney Australia reported fractures in the LRV carbody. There was limited publicly available information about the specific location of fractures within each of these fleets. The inspection of LRV carbody factures and their detection in the Urbos 3 fleets known to OTSI included the following:

- April 2018 – Birmingham, United Kingdom, fractures were discovered in the door portals.
- August 2018 – Sydney, CAF completed inspection of the door portals and windows and did not identify any cracking.
- Late 2019 – Birmingham, fractures detected in the C module underframe RBS and bogie box area.
- February 2020 – Birmingham, CAF determined the root cause of C module underframe fractures were primarily due to bogie RBS contact loading with the underframe RBS which occurred at specific locations[10] on the track.
- May and June 2020 – Birmingham, CAF undertook temporary repairs to the C module bogie box.
- May 2021 – Sydney, CAF completed additional inspections of the door portals and window areas to identify potential fractures. No defects were identified.
- 11 June 2021 – Birmingham, fleet suspended due to fractures detected in bogie box area.
- 14 June 2021 – Sydney, CAF informed TfNSW of the fractures detected in the Urbos 3 Birmingham fleet, reported to be located in the area of 'steel box over bogies'. Advice from CAF was that inspection of the Sydney Urbos 3 fleet was not needed 'as long as the infrastructure, operational and maintenance aspects remain as considered during design phase'. TfNSW sought more details on the fractures and requested a briefing be provided to ALTRAC.
- 15 June 2021 – Sydney, TfNSW forwarded the CAF Birmingham Urbos 3 fleet fracture advice to ALTRAC, Transdev and Alstom.
- 15 September 2021 – Sydney, CAF provided a slide presentation to TfNSW detailing the findings of CAF's investigation into the Birmingham Urbos 3 fractures that included:
    - Bogie RBS can make contact with the underframe resulting in structural damage to the underframe.
    - Vehicles running at correct service speed with RBS clearances to standard do not produce concern with contact loading of the underframe.
    - An increase in service speed on infrastructure with tight curves[11] and no transitions into those curves can cause an increase in rotation stop loading.

[10] Specific locations identified by CAF included track with tight radii curves of a radius less than 50 meters, with no transition curves and where the track speed was above a design limit.

[11] Tight curves on the Birmingham LRV network, UK were noted to have a radius between 25 m and 50 m.

- A reference to the checking of bogie RBS wear contained within the related CAF TMP procedure (BOG-04-005) (paragraph 1.93 b. on page 43).

- 16 September 2021 to 1 October 2021 - Sydney, Transdev Urbos 3 Lilyfield depot was initially closed due to a COVID outbreak with multiple staff required to isolate. Staff from the Randwick depot were employed to carry out a revised general inspection process, which included inspecting the underframe as per the TMP. Most of the staff at Randwick had not inspected Urbos 3 vehicles before. Those staff worked on the Alstom Citadis X05 LRVs that were operated on the Sydney L2 and L3 light rail lines.
- 21 September 2021 – Sydney, CAF provided the same presentation for the Birmingham fractures to ALTRAC and Transdev.
- 27 September 2021 – Sydney, an Alstom maintenance technician detected fracture of the underframe RBS during a routine scheduled 'IS' visual inspection on U2122.[12] The maintenance technician was originally from the Randwick depot and transferred to the Lilyfield depot from 16 September 2021 to carry out IS inspections.
- 28 September 2021 – Sydney, Transdev undertook a risk assessment covering the risk of underframe fracture in the RBS. The results concluded the Urbos 3 could continue operating as there were no fractures in the horizontal welding of the RBS attachment to underframe (Location #1.1 as per Figure 7 on page 17). The risk assessment also recognised that an additional fracture inspection regime was to be implemented to regularly check the RBS area for any increase in fracture damage.
- 7 October 2021 – Sydney, CAF carried out an inspection of 4 Urbos 3 units (8 x C modules) with 22 of 32 bogie and underframe RBS clearances (Figure 5 - B on page 15) identified to be out of tolerance.
- 18 October 2021 – Sydney, CAF recommended an inspection of the bogie box and L brackets for fractures. That inspection involved removal of the internal passenger seating.
- 27 October 2021 – Sydney, Alstom's inspection of the bogie box area identified fractures in some units, with the fleet initially suspended from operation while additional inspections of the remaining fleet was carried out.
- 31 October 2021 – Sydney, operation of the Urbos 3 fleet was confirmed as being suspended following a recommendation made by ALTRAC.
- 8-12 November 2021 – Sydney, CAF identified some minor fractures in the S module window frame area, and C and R module central window pillar.
- May 2022 – Sydney, a fleet wide inspection of the R module bogie box was conducted and found all 12 Urbos units had cracking of varying severity on the top plate of the R module bogie box. CAF proposed a temporary repair to allow the vehicles to return to service for a period of 12 months before the permanent repair was implemented. The temporary R module repair was conducted in parallel with the C module bogie box repairs and became an additional requirement for the Urbos 3's return to passenger service.

1.22 Full details of the timeline associated with detection of underframe fractures are in *Appendix 3: Urbos 3 fracture detection timeline* on page *104*.

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[12] An 'IS' inspection covered the visual inspection of an LRV unit at a 15 day frequency (30 days during the COVID pandemic) in accordance with a list of 'IS' nominated TMP instructions.

Procurement

1.23 OTSI reviewed the Urbos 3 procurement sub processes of Sourcing, Design and Build, and Commissioning.

1.24 TfNSW reported that it implemented a Safety Management System (SMS) for the stages of the Urbos 3 procurement process under its management (steps c. to h. below). The full process involved several key steps including:

Sourcing

a. expressions of interest to the open market

b. shortlisting of tenders required to submit a supply proposal against a request for tender

c. review and assessment of the short-listed tender bids

d. award of a contract to supply and maintain the LRVs

Design and Build

e. review and assessment of the proposed LRV design

f. inspection of the manufacturing process

Commissioning

g. completion of testing and commissioning

h. final acceptance.

Sourcing

Expressions of interest to the open market

1.25 On 29 March 2011, Metro Transport Sydney (MTS), the owner of the Sydney Light Rail System at that time, sought expressions of interest (EOI) on the open market for the supply of light rail vehicles to operate on the network.

1.26 Following the EOI process, CAF and another organisation were invited to tender, with the tender closing on 29 February 2012.

1.27 On 23 March 2012, the New South Wales Government announced that it had purchased MTS. Following the purchase, TfNSW's Transport Projects Division took control of the procurement for additional LRVs and established a project to extend the existing line from its terminus at Lilyfield to Dulwich Hill.

Competitive tendering

1.28 MTS had received 2 tenders but had not opened or evaluated those tenders prior to TfNSW purchasing MTS in 2012.

Evaluation of shortlisted tenders

1.29 An evaluation of the 2 tenders was subsequently conducted by a Tender Assessment Committee (TAC) comprising one TfNSW representative, 2 independents and the CEO of MTS. The TAC had the benefit of specialist advisor reports from internal and external consultants for each of the tenders. Interfleet Technology Pty Ltd (Interfleet) was the external advisor on rolling stock technical aspects.[13] RailCorp experts provided advice on the design, engineering assurance and rail network interface.[14]

Tender evaluation

1.30 The review of the 2 tender submissions recognised both as substantial entities in the light rail market with the CAF LRV design offered on the basis that it was an established design and essentially a 'World Tram'. No concerns were raised regarding either tenderer to deliver safe rolling stock.

1.31 The TAC's evaluation was endorsed by a Tender Review Panel comprising of senior TfNSW personnel from the Transport Projects Division.

1.32 At the time of tender, CAF Urbos 3 LRVs operated in several countries and cities including Spain (Seville, Granada, Cádiz, Málaga and Zaragoza), Serbia (Belgrade) and France (Nantes).

Contract award and LRV supply requirements

1.33 On 1 August 2012, TfNSW awarded the contract to CAF for supply of an initial 6 LRVs to be delivered and operational as a fleet by August 2014. The contract included options to order additional LRVs up to 2 years after the initial fleet became operational. In October 2013 the option to purchase 6 additional Urbos 3s was exercised for the Sydney IWLR line.

1.34 Delivery of the full 12 Sydney Urbos 3 LRVs started on 19 December 2013 with the final LRV entering into service on 3 June 2015.

1.35 Additional Urbos 3 LRVs were also purchased through the supply contract with:

a. Six LRVs delivered for the Newcastle Light Rail Line with the final Light Rail vehicle arriving on 31 July 2018.

b. Four additional supplementary LRVs for the Sydney IWLR line with delivery of the LRVs in August 2023.

1.36 General requirements were detailed within the *LRV specification* for delivery. Relevant information included:

a. Be capable of safe and reliable operation in the LRV operating environment.

b. Be designed and built to internationally recognised standards.

c. Have a minimum design life of at least 30 years.

d. Undertake testing on the LRVs against the defined *IEC-61133 - Railway applications - Rolling stock standard on completion of construction and before entry into service*.

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13 Interfleet were engaged by TfNSW to provide specialist rolling stock technical advisory services to support the procurement activity.

14 RailCorp was the operator of the Sydney passenger trains network up until 31 December 2012. Sydney Trains and NSW Trains were formed from RailCorp and commenced train operations from 1 January 2013.

e. A requirement to: operate on grades and curves found on the existing IWLR line and the proposed extensions to the inner west and the Sydney CBD; and be capable of achieving the same acceleration, deceleration, top speed, comfort levels and door cycle times as the light rail vehicles that operated previously on the IWLR line.

f. A requirement to provide a description of the inter-changeability of motor and trailer bogie components.

1.37 In addition, the contract required submission of a list of the internationally recognised standards used for assessment of dynamic performance, ride quality, shock and vibration along with evidence of the performance achieved.

1.38 The LRV contract required provision of 'Review Documents' that included safety cases for:

a. Design and Construction

b. Test and Commissioning, and Revenue Service.

1.39 The LRV contract also required provision of various 'Safety Plans' including the following:

a. Safety Management and Accreditation

b. Design Management

c. Design Review

d. Testing and Commissioning

e. Configuration Management

f. Technical Maintenance.

1.40 In August 2012, CAF Australia was awarded a contract for the maintenance of the new Urbos 3 LRVs, and existing Variotrams that were in operation on the light rail network at that time. That contract allowed for 3 to 6 months transition from the existing maintainer.

Design and build

CAF design and maintenance requirement documentation

1.41 CAF's tendered detailed design documentation was incorporated into the LRV supply contract as the 'Technical Description'. Relevant assurances and design details provided by CAF within that documentation included the following:

a. All LRV carbody elements were to be designed in accordance with applicable legislation, specific requirements, and for a lifespan of 30 years.

b. Finite element analysis (FEA)[15] calculations were to be made by CAF to validate the design. The FEA calculations were to consider the stress (both static and fatigue) the vehicle would be subjected to over the 30-year lifespan.

c. The carbody structure was to be subjected to strain gauge[16] testing to validate the manufacture and the results obtained from the FEA calculations. In this way, CAF was

[15] Finite element analysis (FEA): a computerised numerical analysis technique used for solving differential equations to primarily solve mechanical engineering problems relating to stress analysis.

[16] A strain gauge is a device used to measure the strain (deformation) of an object when a force is applied. The gauge detects changes in electrical resistance as the object deforms. Strain gauges work by relating the change in resistance of the gauge to the strain in an object.

required to provide assurance that the components, given proper maintenance, would have a useful life of 30 years.

d. The vehicle was designed and built according to internationally recognised standards including:

   i. *EN 12663 Structural requirements of railway vehicle bodies* (the EN 12663 design standard)[17]

   ii. *EN 15227 Crashworthiness requirements for railways vehicle bodies*[18]

   iii. *EN 12299:2009 Railway applications - Ride comfort for passengers - Measurement and evaluation*[19]

   iv. *EN 50215:2001 Railway applications - Testing of rolling stock after completion of construction and before entry into service.*[20]

e. Motor bogies could be interchangeable with one another and between any motor cars furnished under the contract.

1.42 CAF considered the carbody was compliant with the EN 12663 design standard as their FEA *Structural Calculation Report* demonstrated, amongst other things, no significant permanent deformation at any point of the structure under the prescribed design load cases.

1.43 To guarantee a useful life of 30 years for the LRVs, CAF was required to establish a technical maintenance plan (TMP) that defined the periods for servicing and/or replacement of identified components. CAF advised that adhering to its planned service schedule and interventions in the LRV TMP, would ensure appropriate adjustments and replacements were made to deliver optimum operation of the LRVs throughout the 30-year design life.

1.44 CAF's FEA *Structural Calculation Report* was provided to TfNSW as part of design detail information. That report assessed fatigue loading of the LRV underframe and identified the major principal stresses (N/mm^2) within the underframe welded material occurring within a Carbody C1 bogie box location. The calculations of those results identified the:

a. associated weld detail category of 80 – a discontinuous angled T weld with direction of stress as longitudinal

b. allowable fatigue stress limit of 51 N/mm^2 [@10^7 cycles (10,000,000) cycles][21]

c. calculated fatigue stress range with the maximum value at 51 N/mm^2

d. compliance factor of 1 achieving the fatigue stress limit at the location.

1.45 A compliance factor value of 1 represented the minimum compliance factor range that was permissible under the EN12663 design standard to achieve a 30-year design life of 10^7 cycles.

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17 EN 12663-1:2010+A1:2014 - Railway applications - Structural requirements of railway vehicle bodies - Part 1: Locomotives and passenger rolling stock (and alternative method for freight wagons).

18 EN 15227:2008+A1:2010 - Railway applications - Crashworthiness requirements for railway vehicle bodies.

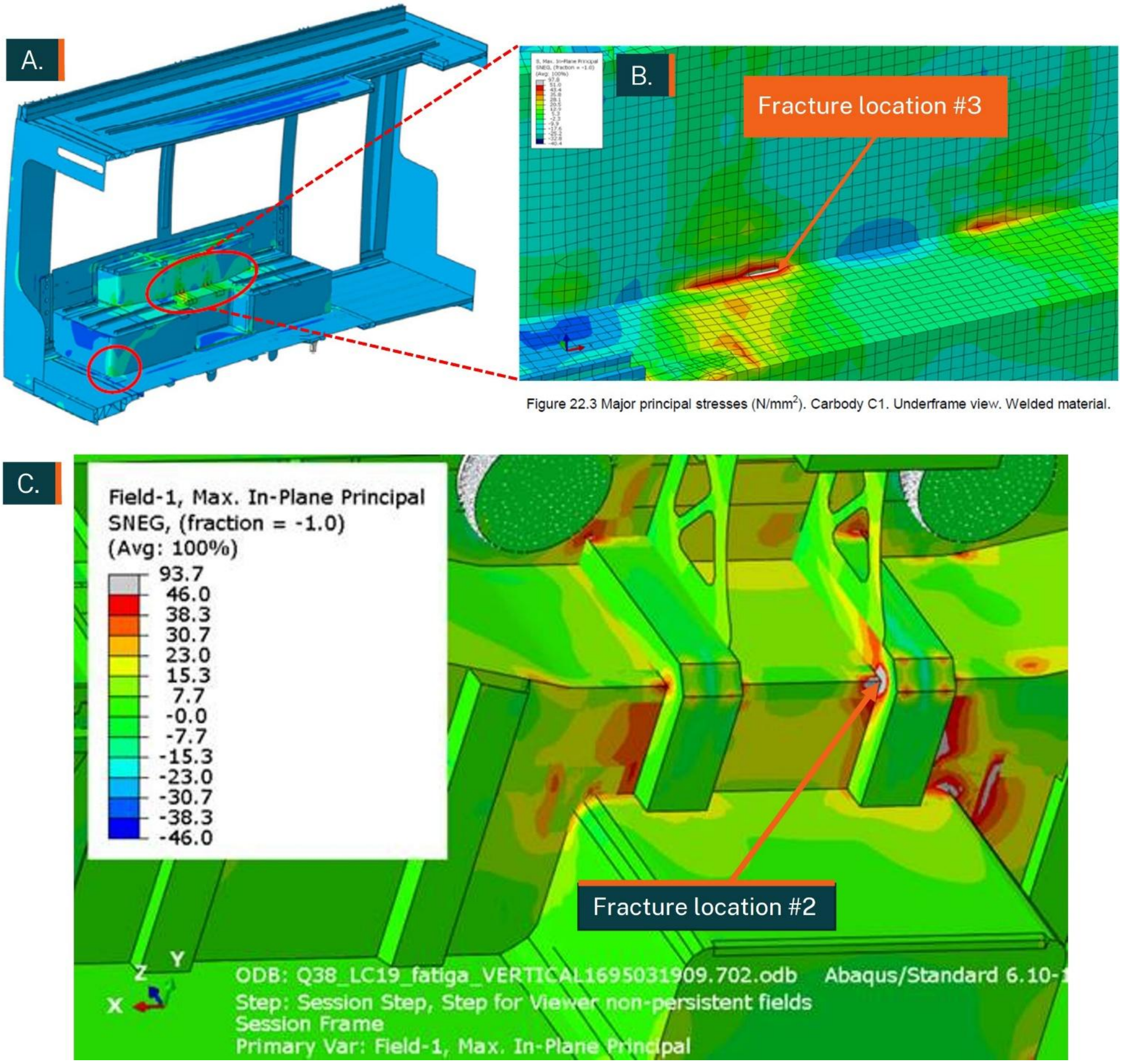
19 EN 12299:2009 - Railway applications - Ride comfort for passengers – Measurement and evaluation

20 EN 50215:2001 - Railway applications - Testing of rolling stock after completion of construction and before entry into service.

21 CAF's *structural Calculation Report* reported that to simplify the analysis stress ranges, distribution plots were limited to the most critical allowable stress range (the one corresponding to a fillet welding under transversal stress [see partial penetration welding 'Y', Ref 5, 23N/mm^2 @ 10^7 cycles (Figure 15 on page 30)] in order to focus the analysis in points with stress ranges above that limit. Although the maximum principle stress of 51 N/mm^2 was out of the limit used in the FEA annex plots for stress in welded material, the specific welding belonged to the category 80 and the allowable limit value of that specific case was 51 N/mm^2 according to the CAF carbody calculation specification. As such that value was below the allowable limit and determined by CAF to be acceptable.

The location of major principal stresses in welded material for the vertical load case was identified in the *Structural Calculation Report* (Figure 13).

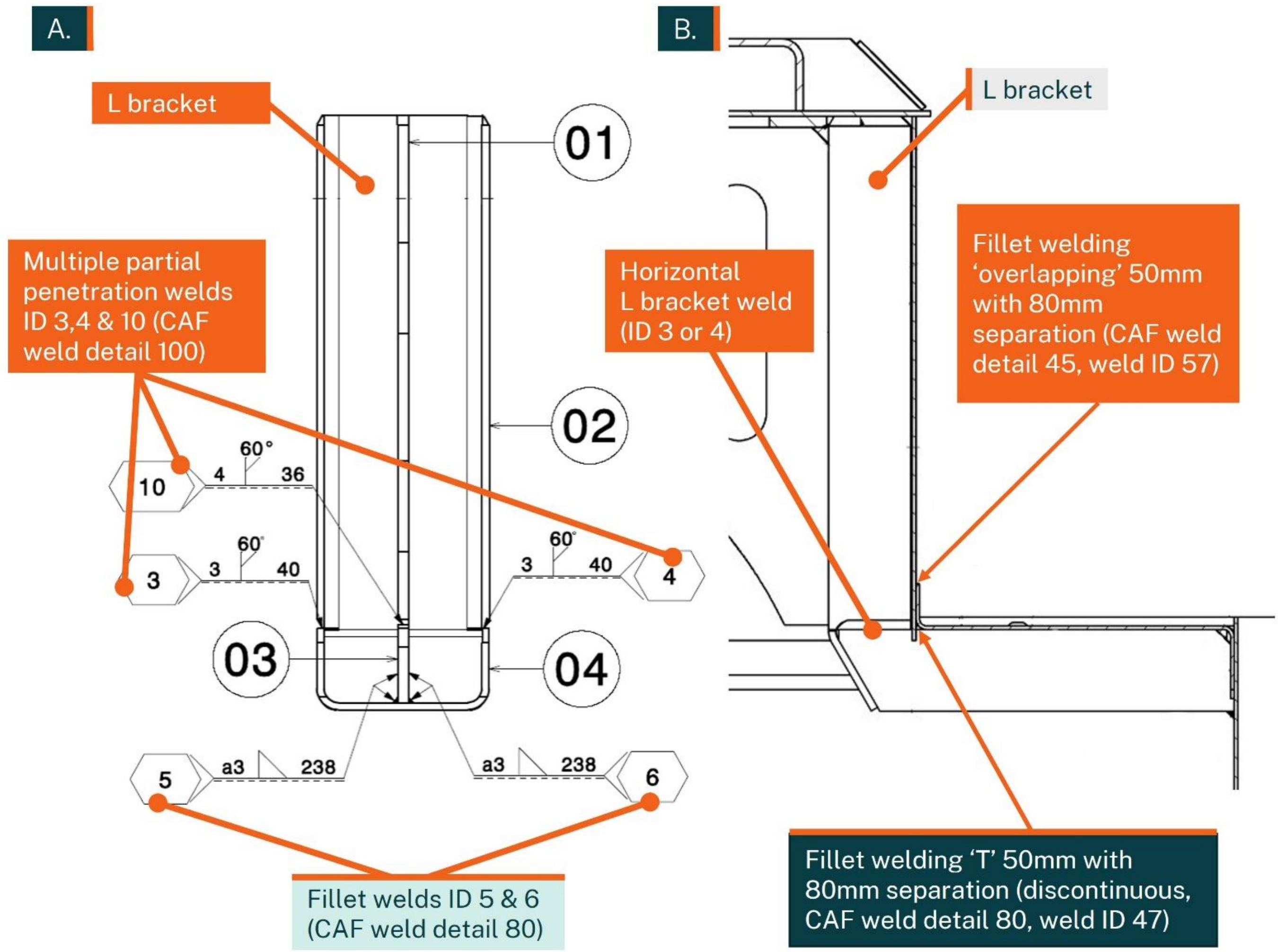
Figure 13: CAF FEA major principal stresses plots of welded material in carbody C1



CAF FEA major fatigue principal stress plots in welded material for the vertical fatigue load case. The plots provided an indication of where the major principal stress resided in the underframe welded structure. Image A: RHS view of Carbody C1 major principal stresses plot in welded material noting the ellipse area where the major principal stress was located in proximity to fracture location #3. Image B: Enlarged view of the stress plot ellipse section with grey shaded area being the major principal stress location in the bogie box structure and its proximity to fracture location #3. Image C: Inverted enlarged view of bogie box area showing section of stress plot where the major fatigue principal stress was located in the vicinity of fracture location #2.
Source: CAF, annotated by OTSI

1.46 The major principal stress of the bogie box in welded material was identified as weld ID 47 (Figure 14 - B). That location being near the coincidence of the upper vertical bogie box sheet interface with the lower shelf (fracture location #3), and the corner of the L bracket structure (fracture location #2) (Figure 4). Details of the L bracket design and welding fabrication obtained from CAF are also depicted in Figure 14.

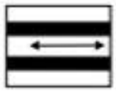
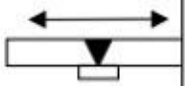
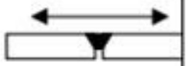
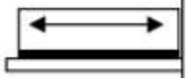
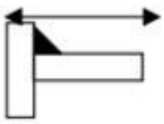
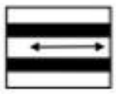
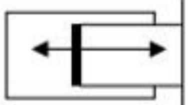
Figure 14: Bogie box L bracket weld construction details



Details of the L bracket weld construction and assembly within the bogie box sheeting. Image A – front view shows weld identification numbers 3, 4, 5, 6 and 10 along with the weld category details that CAF applied in their FEA assessment of the underframe design. Image B – side view shows the L bracket in an assembled position against the bogie box sheeting noting the fillet 'T' weld category detail 80 for weld ID 47 provided by CAF at that weld location and the L bracket horizontal weld ID 3 & 4.
Source: CAF, annotated by OTSI

1.47 The weld detail category references of 80 and 100 were detailed by CAF within its *Structural Calculation Specification* (Figure 15). Weld detail category 80 specified the weld being a discontinuous angled welding 'T' with a force direction of longitudinal. Weld detail category 100 specified the weld being a partial welding penetration 'Y' with a force direction of longitudinal. The Urbos 3 *Structural Calculation Specification* listed the fatigue limits for different weld types incorporated into the Urbos 3 design. Selection of the applicable weld detail category for each weld was dependent on an assessment of the direction of maximum stresses identified through the structure and the orientation of the weld. CAF's assessment of the weld detail categories of 80 (bogie box sheeting weld ID 47) and 100 (L bracket weld ID 3, 4 & 10 (Figure 14) relied on their FEA assessment.

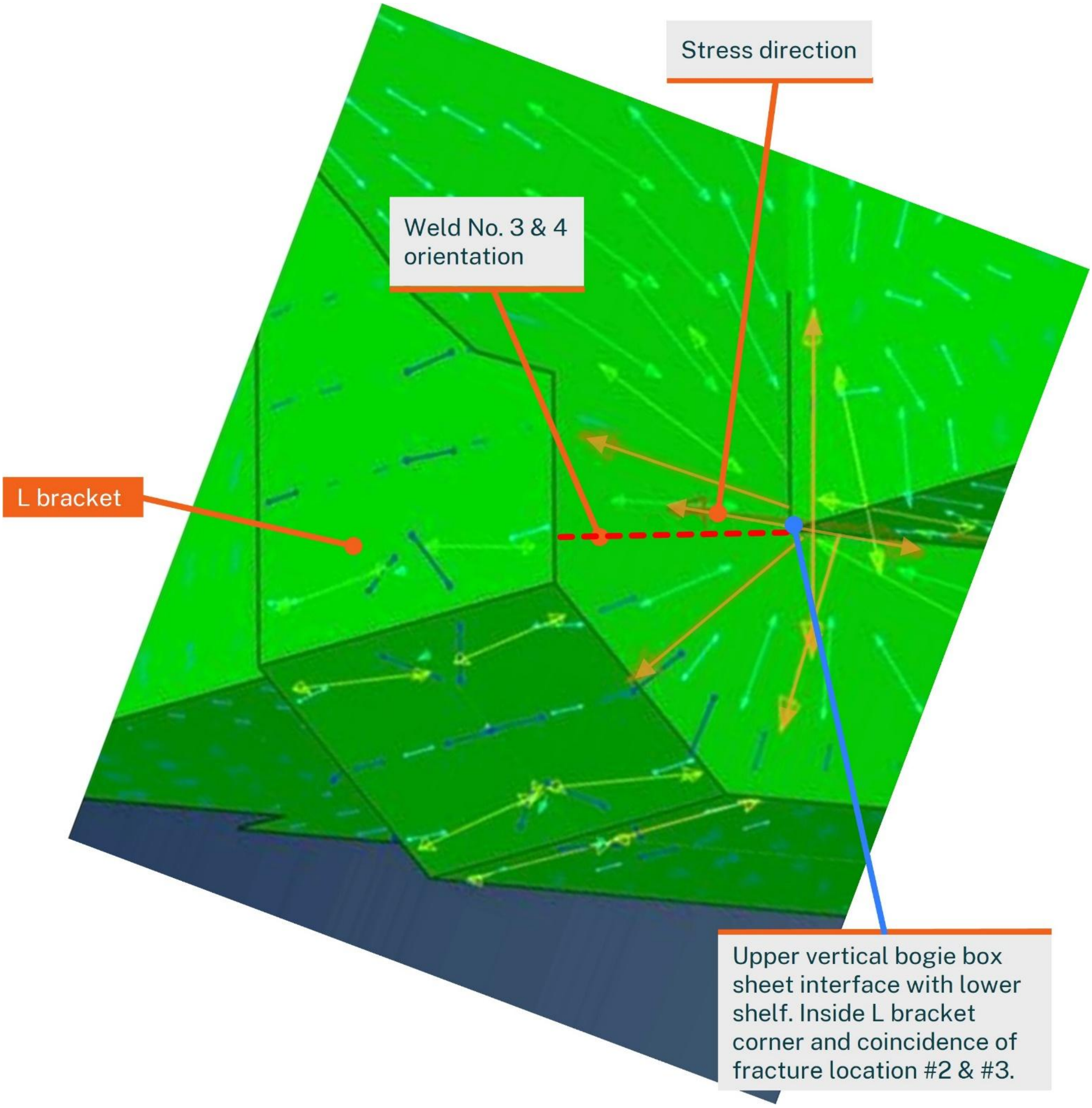
Figure 15: CAF fatigue weld detail category references

Welding type	Force	Ref.	Figure	Detail category	Fatigue limit (N/mm^2) Cycles			
					$5 \cdot 10^4$	10^6	10^7	10^8
Base Material	-	1		160	320	202	103	64.8
Complete welding penetration "V"	Longitudinal	2		100	288	126	64	40.5
	Transversal	3		71	243	89	46	28.7
Partial welding penetration "Y"	Longitudinal	4		100	288	126	64	40.5
	Transversal	5		36	123	45	23	14.6
Angled welding "T"	Longitudinal	6		100	288	126	64	40.5
	Longitudinal Discontinuos	7		80	272	100	51	32
	Transversal	8		36	123	45	23	14.6
Welding in "overlapping" angle	Longitudinal	9		50	171	63	32	20.2
	Transversal	10		45	154	57	29	18.2

Source: CAF, annotated by OTSI

1.48 The FEA assessment detailed the direction of stress (and corresponding force) acting along the weld ID's 3 and 4 as shown in Figure 16. CAF assessed the direction of maximum stress as 57.7 N/mm^2 acting through those welds to be longitudinal and hence a selection of the weld detail category of 100 was made. The same assessment methodology was applied by CAF to select the other bogie box weld detail categories, including the bogie box sheeting weld ID 47 being a weld detail category 80 with a direction of stress as longitudinal.

Figure 16: CAF bogie box L bracket FEA force direction plot



CAF stress/force direction FEA plot of bogie box at the L bracket location for vertical fatigue load case. Stress direction plot showing principal stress directions for bogie box L bracket (orange arrows) and orientation of welding IDs 3 and 4 (red dotted line, weld IDs referenced in Figure 14 on page 29) where fracture location #2 was identified. Orientation of the L bracket weld ID's were parallel to the stress direction indicated by the orange arrows with the stress direction radiating out from the inside L bracket corner where fracture location #2 was identified and on the inside of the bogie box sheeting, where fracture location #3 was identified at the upper vertical bogie box sheet interface with the bogie box lower shelf.
Source: CAF, annotated by OTSI

1.49 The risk of underframe fracture was identified in the design stage with treatment options documented. The risk was assessed as being appropriately treated by CAF and noted by TfNSW. These risk controls were identified:

- resistance of the underframe in accordance with standard EN12663
- FEA assessment
- structural strength testing
- application of a maintenance inspection practice.

1.50 Post incident, and before operation of the modified vehicles, CAF advised the underframe RBS structure was not designed for repetitive impacts in normal operation identifying that impact 'can affect negatively in the carbody shell'. CAF further advised that Urbos 3 RBS clearances (Figure 5 - B) were to be respected to avoid that type of loading in consideration of the design.

1.51 TfNSW required the option to use Urbos 3 bogies as interchangeable components i.e. have the flexibility to interchange bogies between vehicles. This provision was acknowledged by CAF in the tendering phase. However, the ability to interchange the bogies was not accounted for as a standard practice in the maintenance procedures provided during the Urbos 3 vehicle delivery stage. There was no follow-up qualification provided by CAF with respect to the contract requirement not being met. In addition, TfNSW did not identify the absence of a bogie interchange procedure on their review of the maintenance procedures during the commissioning and acceptance stages. Likewise, CAF Australia up to June 2015 and Alstom from July 2015 did not identify the issue during the conduct of vehicle maintenance leading up to the incident date.

LRV operational performance and track maintenance requirements

1.52 In September and October 2012, during the design evaluation process, CAF requested details of the Sydney IWLR LRV operational and track performance requirements from TfNSW. The information supplied by TfNSW included:

a. **Track geometry design requirements**.

CAF requested track geometry details of gradient,[22] radius and cant.[23] TfNSW provided infrastructure construction drawings that detailed the IWLR track geometry design including track curvature radius and track cant which identified curves with and without transition curves.[24] The infrastructure drawings also referenced track design speed and track cant details that permitted the calculation of Droc values.[25] There were a number of curves on the IWLR line that did not contain transition curves and a number of curves that did not contain track cant. Those locations were near stations with 20 km/h speed restrictions applied to reduce LRV speed.

[22] Gradient: A measure of the rate at which the railway is inclined (rising or falling).

[23] Track cant: Generally, the term Cant or Superelevation is used for intended height difference in the rails of track (i.e. where the track is inclined in a curve).

[24] Transition curve: A curve of uniformly varying radii used to connect straight and curved tracks or curves of different radii.

[25] A Droc value denotes the rate of change in track cant deficiency expressed as mm/s. Track cant deficiency is the amount by which the cant of as built track would have to be increased to equal the equilibrium cant in a curve. Equilibrium cant is the theoretical cant when the resultant of the train's centrifugal force at a given speed in a curve and the train's perpendicular vertical force taken across the tops of rails is balanced. In this situation there is no net lateral force on the train.

b. **Line distance and LRV speed profile of the IWLR.**

TfNSW provided line distance and an LRV speed profile for the IWLR as requested.

c. **Track tolerances and maintenance standards.**

CAF requested track wear, misalignment and maintenance standards. TfNSW provided CAF with a copy of RailCorp standard ESC 215 that detailed the kinematic structure gauge which needed to be observed by LRV vehicles.[26] The standard identified that track tolerances specified may differ from those imposed for design or maintenance of track. RailCorp standard ESC 215 referenced the track design and stability standard ESC 210.[27] RailCorp standard ESC 210 contained track geometry damage limits. The related track geometry maintenance intervention standards were contained in another RailCorp standard identified as TMC 203 that was not referenced in ESC 210 at that time.[28] Standards ESC 210 and TMC 203 were not supplied to CAF as per their request. However, the standards were publicly available on the RailCorp Civil Standards website at the time.

TfNSW design evaluation

1.53 A small technical team was established within TfNSW to manage the procurement of the 12 new LRVs including the LRV design evaluation. TfNSW's review team worked with CAF, the TfNSW Chief Engineer and the Engineering Assurance team to develop an equivalent process to the one outlined in the TfNSW SMS,[29] suitable for evaluation of the Urbos 3 LRV design during procurement.

1.54 The scope of the TfNSW design review was to provide the necessary assurance that the detailed vehicle design was compliant with *LRV Specification* requirements and the tendered design documentation.

1.55 Objectives of the TfNSW design review included provision of an assurance that the:

a. vehicle design was suitable for operation on the Sydney Light Rail network

b. vehicle design incorporated industry norms and best practice

c. proposed design was operable and maintainable

d. proposed testing activities were relevant and comprehensive

e. proposed manufacturing processes/activities were satisfactory.

1.56 TfNSW received various CAF design submissions during the design review phase including:

a. underframe assembly drawings

b. bodyshell calculation reports

c. advice assuring the Urbos 3 vehicles had undergone curving force and ride calculations meeting international standards

[26] ESC 215 – Transit space standard Version 4.9 Issued April 2013, Reconfirmed 03 July 2019.

[27] ESC 210 – Track Geometry and Stability - Engineering Standard, Version 4.8, Issued April 2013 Reconfirmed 03 July 2019.

[28] TMC 203 – Track Inspection - Engineering Manual, Version 5.3, Issued April 2013 Reconfirmed 03 July 2019 - TMC 203 was adopted by Alstom to manage inspection and rectification of track geometry defects identified during IWLR line maintenance activities.

[29] The applicable TfNSW SMS included the procedures of TSR T1 - Technical Management and 4TP-PR-209 – Engineering Assurance Review of Project Submissions.

d. a FEA summary report (*Structural Calculation Report*) to show compliance with international standard *EN 12663 – Structural Requirements* for the Urbos 3 carbody. The results of the FEA summary report concluded that stresses were below the maximum allowable values specified for each material with compliance to the standard, thereby guaranteeing a fatigue life to 10^7 cycles. The target of fatigue life to 10^7 cycles corresponded to an operational life of 30 years.

1.57 The EN 12663 design standard specifically recognised the rolling stock class of an LRV with low floor design and limited suspension such as Urbos 3. The standard noted fatigue loads acting on the vehicle body structure could differ significantly from the load values provided in the standard. The standard recommended fatigue calculations be derived from multi body-simulations, previous experience, or test measurements for the operating conditions to be expected.

1.58 TfNSW's design assessment reported the Urbos 3 designs, and associated internationally recognised standards, adopted by CAF were reviewed by competent and experienced rolling stock engineers at multiple stages throughout the procurement process. The international standards applied by CAF were applicable at the time and for the vehicle design.[30]

1.59 The TfNSW design review assessed the CAF Urbos 3 design as an established product operating worldwide, suitable for the Sydney operating environment and industry norms for rolling stock procurement projects. During the design review assessment, TfNSW staff attended 2 series of formal design review workshops in late November 2012 and May 2013. These meetings and discussions allowed TfNSW staff to gather more information on the Urbos 3 design, understand the logic behind design proposals, and agree on how to resolve issues, questions or clarifications raised.

1.60 During the design review assessment TfNSW reported that detailed design reviews were carried out on a total of 158 design submissions, with each submission reviewed for compliance with the *LRV Specification*, the *Technical Description*, and suitability for the Sydney operating environment.

1.61 TfNSW queried the *Structural Calculation Report* during the design review. These queries aimed to clarify aspects of the underframe that had a compliance factor near to, or equal to 1. CAF provided more information which satisfied the TfNSW queries, and the issue was closed. At the time of the design review, there were no questions regarding the bogie box sheeting and L bracket design.

1.62 The TfNSW design review accepted the CAF FEA analysis review based on the *Structural Calculation Report* submitted and concluded that the design of the Urbos 3 LRVs was appropriate for the Sydney Light Rail operation. Final verification of the vehicle suitability was to be undertaken and documented in Test Reports and the TfNSW final Safety Assurance Report. Completion of the design review assessment occurred on 20 December 2013.

Urbos 3 Manufacture

1.63 Manufacture of the Sydney Urbos 3 carbody components for the first unit commenced in March 2013, with those components progressing into the paint facility by April 2013. TfNSW visited the CAF manufacturing facility in Spain during April 2013. They reviewed the welding

[30] The standards applied by CAF at the time of design also matched the TfNSW light rail standards introduced in 2017 and were current as at the incident date.

process, welder's qualifications and quality process applied to the Urbos 3 manufacturing line and considered them as acceptable. TfNSW also reviewed manufacturing of vehicle components for the Birmingham fleet and as built documentation for supply of the Urbos 3 to other countries. The TfNSW site visit did not review the construction of the Sydney Urbos 3 fleet as the carbody components for the Sydney fleet were not on the assembly line at the time of the inspection.

1.64 Manufacture of the Urbos 3 underframe was subject to a quality system that applied to welding fabrication. CAF's weld quality inspection requirements called for a 100 per cent visual inspection (VT) of all bogie box welds in an assembled configuration on the first vehicle manufactured. The remaining LRVs were subject to inspection of 25 per cent of welds.

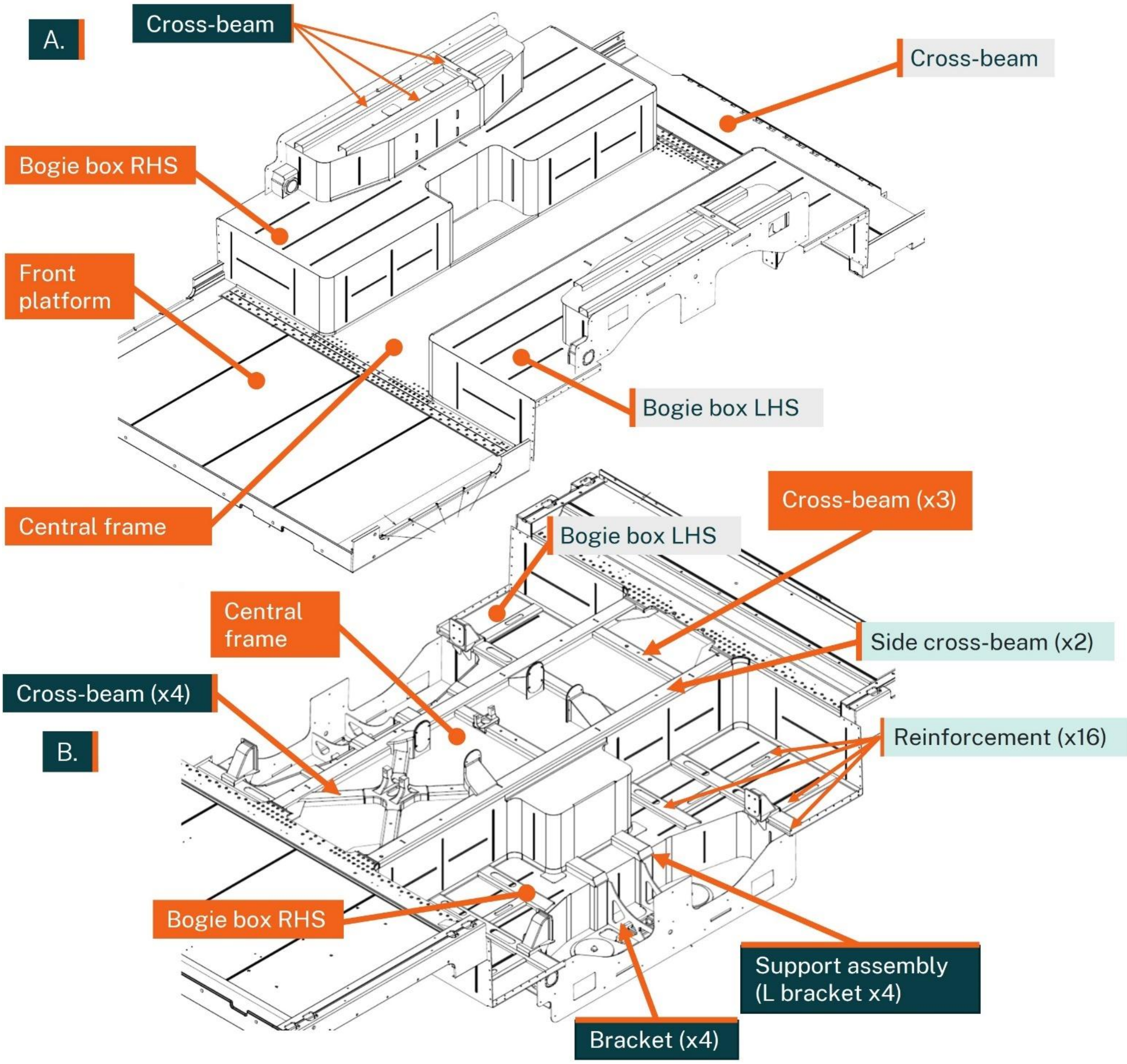
1.65 According to CAF weld certification documents, the L bracket welds (Figure 14 – A) were subject to a visual inspection on the outside surface of the L bracket as they were in the fully assembled state. The visual inspection process at that stage of construction could not view the inside of the L bracket channel where a check of internal welding and plate alignment could have been undertaken. A visual inspection of the central upper bogie box sheet interface with the lower shelf weld (fracture location #3) was also not possible where the L bracket was welded against that section of the bogie box sheeting.

Urbos 3 Underframe and bogie configuration details

1.66 Details of the Urbos 3 C module general underframe assembly are shown in Figure 17. The underframe in the vicinity of the bogie box comprised of 4 main components: 1) the front platform, 2) bogie box (both left-hand (LHS) and right-hand side (RHS)), 3) central frame and 4) a cross-beam (Figure 17 – A).

1.67 Of particular note was the descriptions used in CAF's assembly drawings for the underframe. The central frame was identified to contain cross-beams and side cross-beams. The bogie box was described to contain; cross-beams on the top of the bogie box structure (Figure 17 - A), reinforcements on the inverted side of the bogie box structure (Figure 17- B) and support assembly (being the L bracket) (Figure 17 - B). The descriptions of these parts of the central frame and bogie box structures did not appear within the Technical Maintenance Plan instructions (see *Technical maintenance plan requirements*).

Figure 17: C module underframe assembly

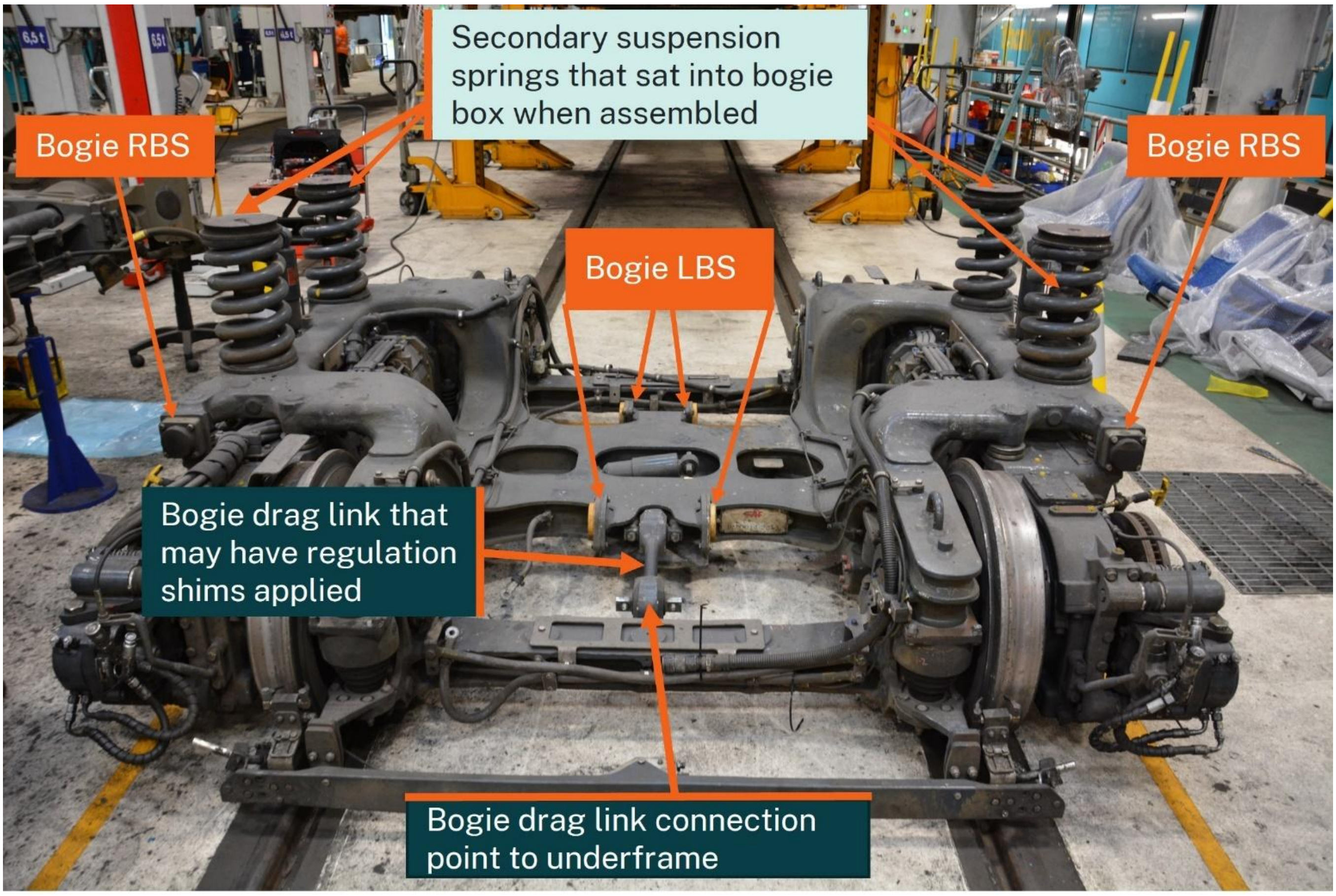


C module underframe bogie box assembly with adjoining components described as per CAF drawing terminology. Image A depicts the front platform, bogie box left and right sides, central frame, cross-beam and bogie box cross-beams located on the top of the left and right side bogie box. Image B depicts the underframe assembly inverted with the central frame and left and right-side bogie box cross beams, brackets and reinforcement members shown.
Source: CAF, annotated by OTSI

1.68 The primary load of the Urbos 3 LRVs was supported through the bogie box assembly area, with the LRV carbody load transmitted through secondary suspension coil springs onto its bogie (Figure 18).

1.69 The suspension springs were mounted into the bogie box underframe area within the spring seating pads (Figure 8 on page 18).

Figure 18: C module bogie



C module motor bogie removed from LRV unit noting bogie RBS, bogie drag link that attached to the underframe pivot assembly, bogie Lateral Bump Stop (LBS) and suspension springs that sat into bogie box spring seating pads when a bogie was placed under the LRV. Source: OTSI

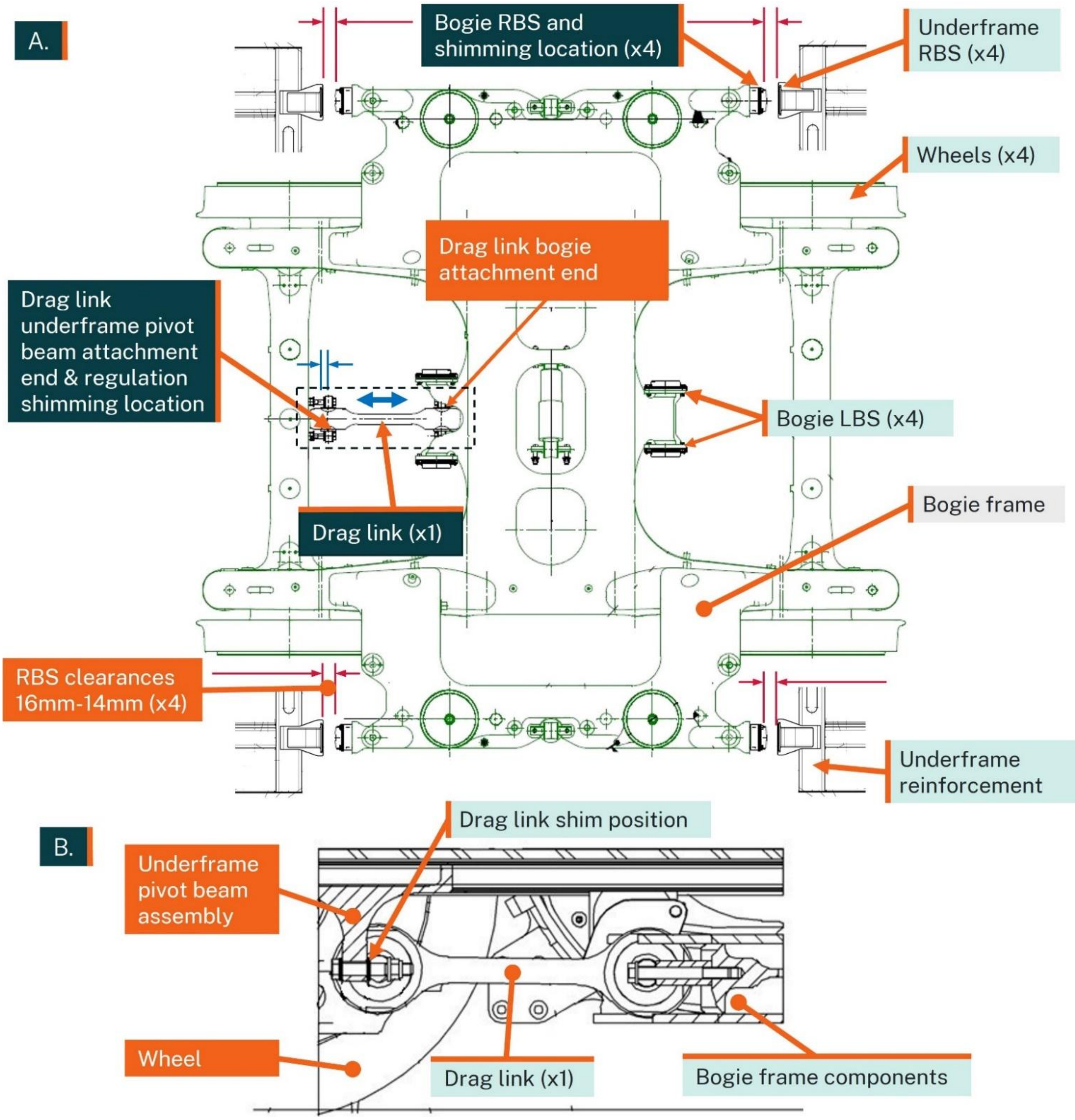
1.70 Set up of the RBS clearances could be achieved through regulation shimming of the drag link[31] and bogie RBS (Figure 19). Any changes in shimming of the bogie RBS would result in a change in the RBS clearance. Regulation shimming of the drag link had the potential to change all 4 RBS clearances. Rotation of a bogie around a curve had the effect of reducing one set of diagonal bogie to underframe RBS clearances and increasing the opposite set of diagonal RBS clearances. Control over regulation shimming arrangements of the C module bogie was necessary to ensure all RBS clearances were within maintenance tolerances.

1.71 RBS clearances were initially set between 14 mm to 16 mm during their manufacture in 2013. A RBS (4 per bogie) could be shimmed by up to 5 mm as per the TMP (see *Technical maintenance plan requirements* on page 42 - *Rotation Stop – Change BOG-04-507 procedure*). That shimming may have occurred at either the LRV manufacture (2013) or during its maintenance. If shimming was not removed or RBS clearances were not checked when a bogie was interchanged under another C module, the resulting RBS clearance could recommence at 9 mm. There were no TMP instructions covering the potential to change drag link shimming. However, if that shimming arrangement also changed during a bogie change the resulting RBS clearance could recommence at less than 9 mm.

[31] Drag link: a longitudinal connecting rod between the bogie frame and carbody underframe.

1.72 Lateral movement of the C module bogie was restrained by 4 bogie lateral bump stops (LBS) that could have come into contact with any one of the 4 underframe LBS (Figure 18 and Figure 19). No fractures were found in the underframe LBS locations and their clearances were not identified as being connected to the occurrence of underframe fractures.

Figure 19: C module RBS clearance and regulation shimming



C module bogie and underframe RBS and drag link clearance arrangements. Image A shows a plan view of the C module bogie arrangement noting the RBS clearance locations and bogie clearance shimming locations at the RBS and drag link. Drag link regulation shimming could be placed at the underframe attachment end changing the bogie position (blue arrows and blue clearance measurement lines) relative to the underframe affecting all RBS clearances (red clearance measurement lines). Image B shows a side cross-section view of dotted area in Image A of the underframe, drag link and bogie frame connection and the drag link shim location that can change all four RBS clearances.
Source: CAF, annotated by OTSI

1.73 Factory certification of Urbos 3 C modules was documented in a type and routine testing procedure that checked key dimensions and configuration details. Results of the RBS clearances were recorded within the type and routine testing certification documentation. The shimming arrangements for each bogie RBS and drag link was not recorded.

Commissioning

TfNSW safety assurance review

1.74 TfNSW completed a safety assurance review for the supply of the Urbos 3 LRVs. TfNSW documented the results of that review in a Safety Assurance Report (SAR).

1.75 TfNSW advised the key steps of the safety assurance review relevant to the investigation included:

- Preliminary hazard analyses to support development of the design specification and to demonstrate that the design would deliver the safety requirements. This step involved conducting hazard identification workshops early in the design phase to review safety risks and mitigation strategies which CAF then built into the design.
- Safety reviews to assess whether the design met safety requirements and to identify additional mitigation measures necessary to ensure identified risks were managed to the specified level before final acceptance of the LRVs.
- Setting out the requirements for the commissioning and operational readiness stage of the procurement.
- Validation of management of risks via safety cases documented by CAF reporting that safety requirements were adequately addressed by the objective evidence gathered through testing and commissioning activities.

1.76 The SAR was intended to demonstrate that adequate testing, commissioning, and operational readiness processes were carried out to ensure that the LRVs operated safely so far as is reasonably practicable (SFAIRP). The SAR was also used by TfNSW's Transport Projects Division (TPD) to demonstrate that it had fulfilled its obligations as a supplier, so that the light rail operator would accept the LRVs for operation and maintenance.

1.77 As part of the safety assurance review, TfNSW assured itself that CAF had documented the risks of LRV operation within a hazard log developed from its risk management process. That hazard log included the risk of underframe failure. CAF also defined various safety arguments which were documented at the design, testing and maintenance phases to manage the risks contained in the hazard log. Those safety arguments outlined the safety measures (controls) assessed by CAF to be suitable to manage the risk of underframe failure. The CAF Hazard Log was included within the TfNSW SAR. The TfNSW SAR was provided to the Office of the National Rail Safety Regulator (ONRSR) as part of TfNSW's accreditation obligations.

1.78 The CAF hazard log for the risk of underframe failure identified static weight tests, structural strength tests and periodic maintenance inspections of the LRV's carbody structural elements to be observed at defined frequencies. These were to be included in the Urbos 3 TMP.

1.79 The TfNSW SAR also noted IWLR line track curvature, speed and curve profiles were provided as part of design documentation to CAF during the design stage. The TfNSW SAR was completed on 17 July 2014.

Testing, commissioning and LRV acceptance

1.80 Prior to TfNSW accepting the Urbos 3 LRVs, CAF completed tests on several vehicles at the factory and on the IWLR line. The results and certifications of those tests were provided to TfNSW to incorporate into their safety assurance review.

1.81 The tests and certification records considered relevant to the investigation included the following:

a. Routine factory leveling test where the RBS clearances were checked and certified to be within tolerances (Q43.92.501)

b. *Ride Comfort and Safety Against Derailment* (Q.43.92.313)

c. *Carbody Strain Gauge Test Report* (Q43.92.101.50)

d. Construction measurement and inspection records including welding records.

1.82 CAF completed static carbody strain gauge testing with strain gauges to be installed at the highest stress points on the carbody structure.[32] Placement of the strain gauges in the vicinity of the bogie box and underframe are detailed in *Appendix 4: Urbos 3 static strain gauge testing 2012* on page 109.

1.83 CAF determined the results from the *Carbody Strain Gauge Test Report* met the EN 12663 design standard requirements for stress-strain behaviour of the LRV in the gauge positions selected. Results of the strain gauge testing for the vertical fatigue hypothesis in the vicinity of fracture locations #2, #3 and #4 are detailed in Table 1.

Table 1: Static strain gauge vertical fatigue results in proximity to OTSI fracture locations

Fracture location	Gauge ID	Hypothesis ΔƠ[MPa]	Admissible ΔƠ[MPa]	Weld detail category
#2	9	23.5	103	Base Material
	10	23.2	103	Base Material
#3	56	8	51	80
	93	15.4	103	Base Material
	146	34.7	103	Base Material
	149	17.0	103	Base Material
#4	55	35.4	51	80

Urbos 3 static strain gauge vertical fatigue results in proximity to OTSI fracture locations. Gauge ID refers to the gauge identification numbers used by CAF in the static strain gauge placement. Hypothesis ΔƠ[MPa] refers to the value of fatigue in MPa (N/mm^2) calculated at the respective strain gauge location. Admissible ΔƠ[MPa] refers to the fatigue limit in MPa that provides for a 30-year fatigue life of 10,000,000 cycles at the respective strain gauge location. Weld detail category denotes the weld category applied by CAF, as referenced in Figure 15 on page 30, to calculate the Hypothesis ΔƠ[MPa] that considered the direction of force applied at the strain gauge location. Source: CAF

32 The static strain gauge testing used strain gauges that measured stress in a single direction consistent with the gauge alignment on the surface being tested.

1.84 The gauges nearest to fracture locations #2 and #3 (gauges 9, 10, 93, 146 and 149) were assessed against the weld category of 'Base Material' (fatigue limit 103 MPa at 10^7 cycles) (Figure 15). Selection of that weld detail category identified the assessment of stress at those gauge locations were not associated with stress in welded material.

1.85 Some of the gauges nearest fracture locations #3 and #4 (gauge 56 and 55) were assessed against the weld category of '80' (fatigue admissible limit 51 MPa at 10^7 cycles). There was no strain gauges located in close proximity of the maximum principal stress in the welded material shown in Figure 13 on page 28. Selection of the weld detail category 80 for the gauges nearest to fracture location #3 was consistent with the value used by CAF in their 2013 *Structural Calculation Report* at the major principal stress (N/mm^2) location within the underframe welded material (see *paragraph 1.44*). That location being identified by CAF to have a direction of stress in the longitudinal. Strain gauges 55 and 56 were orientated in a direction consistent to measure longitudinal strain at their respective locations.

1.86 The EN 12663 design standard recommended that acceleration values and interface forces between low floor vehicle body and bogie be derived from multi body-simulations, previous experience or test measurements for the operating conditions to be expected. The standard also recommended on-track service testing when analysis (FEA design analysis) or static testing did not shown compliance with the design standard or there was uncertainty in the applicable dynamic inputs. On-track service testing using strain gauges was to cover all critical areas according to the results of the structural analyses and/or static testing. Although not being a mandatory requirement of the EN 12663 design standard, the validation of the Urbos 3 fatigue design by on-track testing did not occur on the IWLR line during the commissioning evaluation stage. CAF relied on their FEA assessment and static strain gauge testing to meet the EN 12663 design standard requirements.

1.87 CAF supplied TfNSW with an on-track dynamic ride test report identified as *Ride Comfort and Safety Against Derailment* (Q.43.92.313). The report detailed the Urbos 3 LRV satisfied the dynamic behaviour and ride comfort type testing requirements on the IWLR line as of June 2014 and as per international standard and code.[33] The report also concluded safety and running behaviour for maximum load was considered appropriate with reference to the standards. The report did not recommend any changes to the LRV operational speed or make comment on the infrastructure condition (extent of track defects) at that point in time.

1.88 In addition to the CAF testing and commissioning activities carried out on the Urbos 3 LRVs, TfNSW developed and implemented an acceptance testing program of their own that applied to all LRVs prior to their final acceptance. That testing regime focused on the LRVs meeting operational performance requirements and did not include any LRV on-track strain gauge dynamic testing.

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[33] CAF ride quality testing report (*Ride Comfort and Safety Against Derailment)* referenced EN 12299 Railway Applications – Ride comfort for passengers – Measurement and evaluation. April 2009 and UIC CODE 518 Testing and approval of railway vehicles.

IWLR Urbos 3 maintenance regime and operation

Maintenance history arrangements

1.89 Initially, CAF Australia was the maintainer of the Urbos 3 LRVs from their delivery in December 2013 to June 2015 under contract to TfNSW the asset owner. As the manufacturer, CAF specified the maintenance arrangements[34] for the Urbos 3 LRVs in the TMP. However, ownership of the TMP resided with TfNSW under the supply contract. Once the TMP was received from CAF, TfNSW managed the review and approval of the maintenance standards to deliver the TMP, with essential technical updates provided by CAF or any other technical input managed by TfNSW.

1.90 Documentation provided by CAF in its tender stated the TMP and maintenance instructions contained all the information needed to carry out the scheduled and arising (corrective) maintenance of the LRVs. That included the assembly and disassembly instructions, adjustments and tests required for the LRVs once in operation. The Urbos 3 TMP was originally translated from Spanish to English, with an English version provided as part of the Urbos 3 delivery in 2013.

1.91 Responsibility for the operation and maintenance of the LRVs was initially transferred from TfNSW to Transdev on 22 July 2014 and then to ALTRAC on 1 July 2015. As a part of that transfer TfNSW provided Transdev with the TMP and certification of the Urbos 3 vehicle status via a handover process.

1.92 Accreditation for the Urbos 3 operation and maintenance followed a different timeline. Rail Safety National Law accreditation for the operation and maintenance of the Urbos 3 was transferred to ALTRAC in August 2018 from Transdev, who held the accreditation from July 2014 to August 2018.

Technical maintenance plan requirements

1.93 CAF developed Urbos 3 maintenance documentation relating to the inspection and condition assessment of the; underframe, underframe RBS and bogie RBS. The documentation also covered inspection of the respective RBS clearances and other underframe components. The related TMP instructions included the following:

a. **Bogie RBS and underframe RBS inspection:**[35] LRV C module motor bogies required an inspection nominally every 15 days, with the bogie fully assembled and under the LRV positioned '*on an inspection pit*'.[36] The intent of that procedure was to provide for a visual inspection of the bogie. Inspections carried out against the procedure required a review of the LRV bogie RBS condition (Figure 18 on page 37 and Figure 19 – A on page 38). If the condition of the bogie RBS required replacement it was to be changed. A check of the bogie lateral bump stop (LBS) condition was also to be carried out as part of the procedure. That check required a visual inspection of the surfaces of the support where

[34] Maintenance arrangements being the maintenance tasks to be completed in accordance with approved instructions to be carried out at defined intervals (frequencies).

[35] Sydney Metro Tram – **Bogie – Inspect Visually** - Maintenance Manual – Instruction - BOG-00-001 Rev:4 – 2016 Feb.

[36] An inspection pit provided for a walkway beneath rolling stock to carry out maintenance tasks including the conduct of a visual inspection. See Figure 5 on page 15 depicting an LRV on an inspection pit.

the LBS acted (the underframe) for damage such as cracks or fissures[37] (Figure 20). A similar requirement to check where the bogie RBS acted on the underframe (i.e. the underframe RBS) was not specified in the procedure.

b. **Bogie RBS wear check:**[38] The TMP identified a requirement to check for wear in bogie RBS at every 'P1' inspection, that is, every 70,000 km with the LRVs being subject to approximately 7 inspections since entering into service in 2014.[39] Replacement of the bogie RBS was required if the wear was measured to be greater than 7 mm (RBS free height below 16 mm). There was no requirement within the instruction to record the bogie RBS free height measurement or to measure the bogie RBS clearance with the underframe and record such measurements. Recording of this measurement would have verified the RBS clearance was as per the CAF design tolerance.

c. **Bogie RBS change:**[40] A new bogie RBS fitted to the C module motor bogie was to be measured checking the RBS free height (23+/-0.5 mm) and bogie RBS clearance (14-16 mm). If the bogie to underframe RBS clearance was greater than the required dimension, then the instruction required fitment of a shim. There was no requirement within the instruction to record the initial RBS clearance measurement or final set-up measurement. A maximum of 5 x 1 mm shims could be applied to the RBS configuration, if needed, to obtain the required 14-16 mm clearance.

Application of the bogie RBS change procedure and subsequent checking of the RBS clearance was dependent on the need to replace the RBS. If the RBS free height was measured in compliance with the maintenance tolerance, then there was no requirement to change out the component, or in turn measure the RBS clearance between the underframe and bogie RBS surfaces. In February 2016 the bogie RBS change procedure was amended to remove the requirement for an RBS to be automatically replaced, with replacement of each RBS then being based on the wear/condition requirements. The amendment to the procedure was agreed to by CAF and approved by TfNSW noting the RBS were 'easy to change on-train on condition'. Removal of the automatic replacement requirement of an RBS after every 70,000 kms effectively stopped the ongoing measurement of RBS clearances unless an RBS was replaced.

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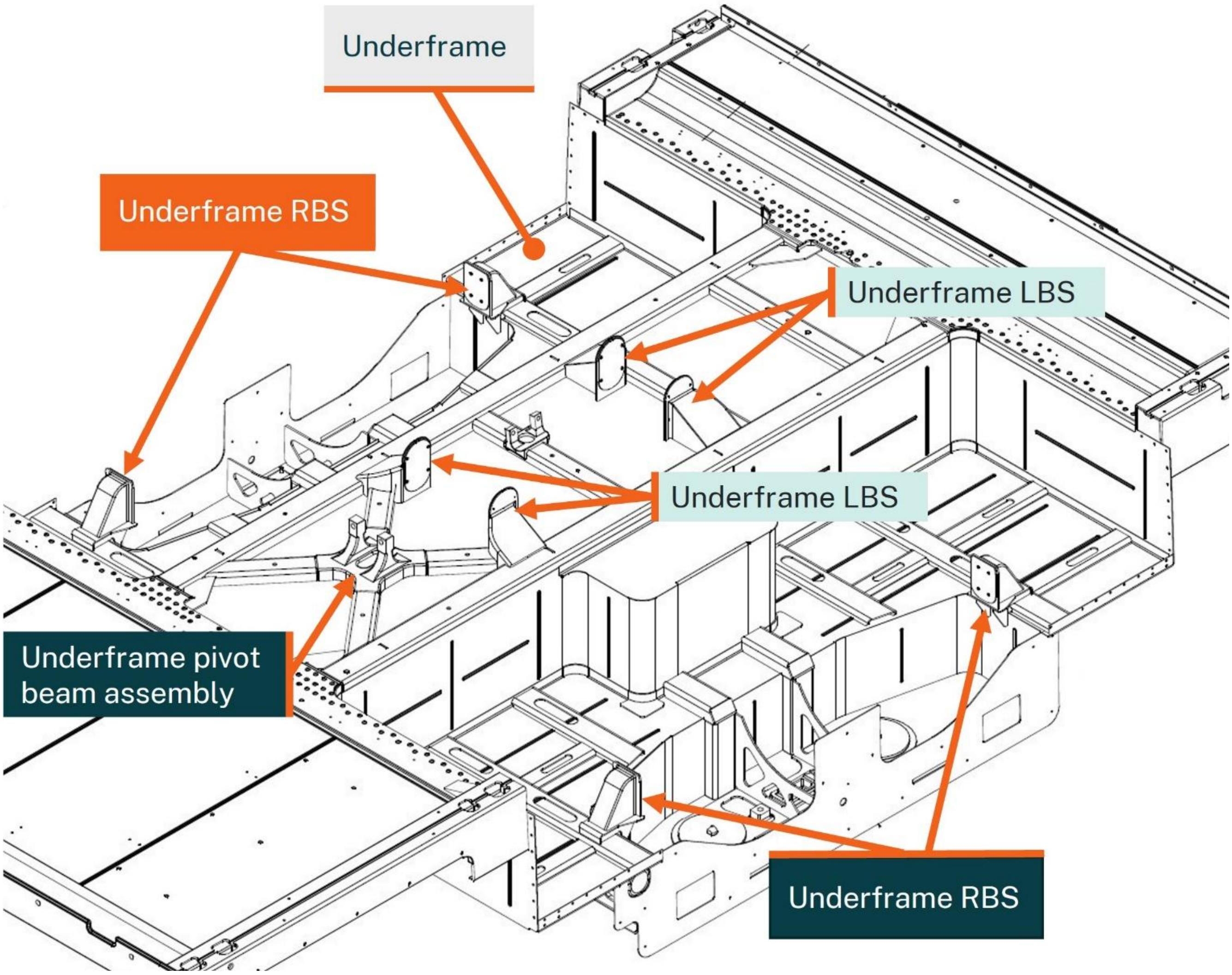
[37] Fissures may be referred to as fractures in metal.

[38] Sydney Metro Tram – **Rotation Stop – Check Wear** - Maintenance Manual BOG-04-005 Rev:4 – 2016 Feb.

[39] The LRV TMP and TMP frequencies was defined in the TfNSW documents Section 3 – Frequencies MI-03 and Section 4 – Maintenance Plan MI-04 as initially produced by CAF.

[40] Sydney Metro Tram – **Rotation Stop – Change** – Maintenance Manual BOG-04-507 Rev:4 – 2016 Feb.

Figure 20: Underframe RBS, LBS and pivot beam details



Inverted view of underframe identifying RBS, LBS and pivot beam assembly locations
Source: CAF, annotated by OTSI

d. **Motor Bogie – Change:**[41] There was no requirement to check the bogie and underframe RBS clearance (4 measurements) at either removal or reinstallation of a bogie. A note of any drag link regulation shimming was required during a motor bogie change along with ensuring the bogie was reinstalled with the same amount of regulation shimming. CAF advised that a motor bogie could not be interchanged with a different motor bogie based on the drag link shimming requirement (Figure 19 on page 38 depicting the bogie drag link and regulation shim locations). CAF also advised the motor bogie change procedure was written considering the fact that the same bogies returned to the same C module. There were no warnings within the procedure to preclude the interchanging of motor bogies. Alstom permitted motor bogies to be changed between LRV units.

[41] Sydney Metro Tram – **Motor Bogie – Change** - Maintenance Manual – Instruction - BOG-00-501 Rev:4 – 2016 Feb.

e. **Motor Bogie – Reassemble:**[42] The procedure specified the process for reassembly of a bogie[43] and referred to the procedure for checking the wear and clearance of bogie RBS by virtue of its reference to the RBS wear check procedure. The recording of RBS clearances (4 per bogie) was not specified in the procedure despite there being a requirement to measure the clearance on reassembly of the bogie. The requirement to measure the bogie RBS clearance to the underframe within this procedure appeared premature as there was no reference within the procedure that the bogie was to be placed under the vehicle at the time of actioning the procedure.

f. **Drag Link – Change:**[44] The procedure covered removal and replacing the drag link with a requirement to register the regulation shimming to ensure the same shimming configuration was reinstalled on fitment of the drag link to the carbody.

g. **Underframe – Inspect Visually:**[45] A visual underframe inspection was required every 15 days as an 'IS' inspection to check for deformation, cracks or breakage of 'longitudinal' or 'cross members' and 'carbody brackets'. The inspection operation was to 'be performed with the entire unit into the moat' (that being the LRV positioned on an inspection pit, Figure 5 on page 15). The inspection also required checking for loose cables, pipes and supports, and to visually check that all components were correctly fastened to the underframe. The full scope of the procedure (checking for fractures and loose components) required checking of the underframe from both outside and within an inspection pit (the moat) (Figure 5 on page 15 and Figure 6 on page 16 depicting partial underframe inspection views from outside the inspection pit). The carbody side skirts needed to be raised to facilitate the entire underframe inspection scope.

The procedure did not include a labelled figure to identify those parts of the underframe to be inspected for fractures. In the absence of a labelled figure, and considering the CAF assembly drawings terms, Alstom interpreted the central frame required inspection for fractures (Figure 21 - green shaded region). That scope of the inspection was to be carried out by a technician viewing the underframe from within an inspection pit. The longitudinal (side cross-beam),[46] cross members (cross-beam),[47] underframe LBS (carbody bracket),[48] underframe lateral damper bracket (carbody bracket) were to be inspected for fractures as a part of the inspection.

[42] Sydney Metro Tram – **Motor Bogie – Reassemble** – Maintenance Manual – Instruction – BOG-00-008 Rev:4 – 2016 Feb.

[43] Reassembly of a bogie is the assembly of bogie components to make a complete bogie ready for reinstallation under an LRV C Module.

[44] Sydney Metro Tram –**Drag Link – Change** - Maintenance Manual - BOG-04-504 Rev – Feb 2016.

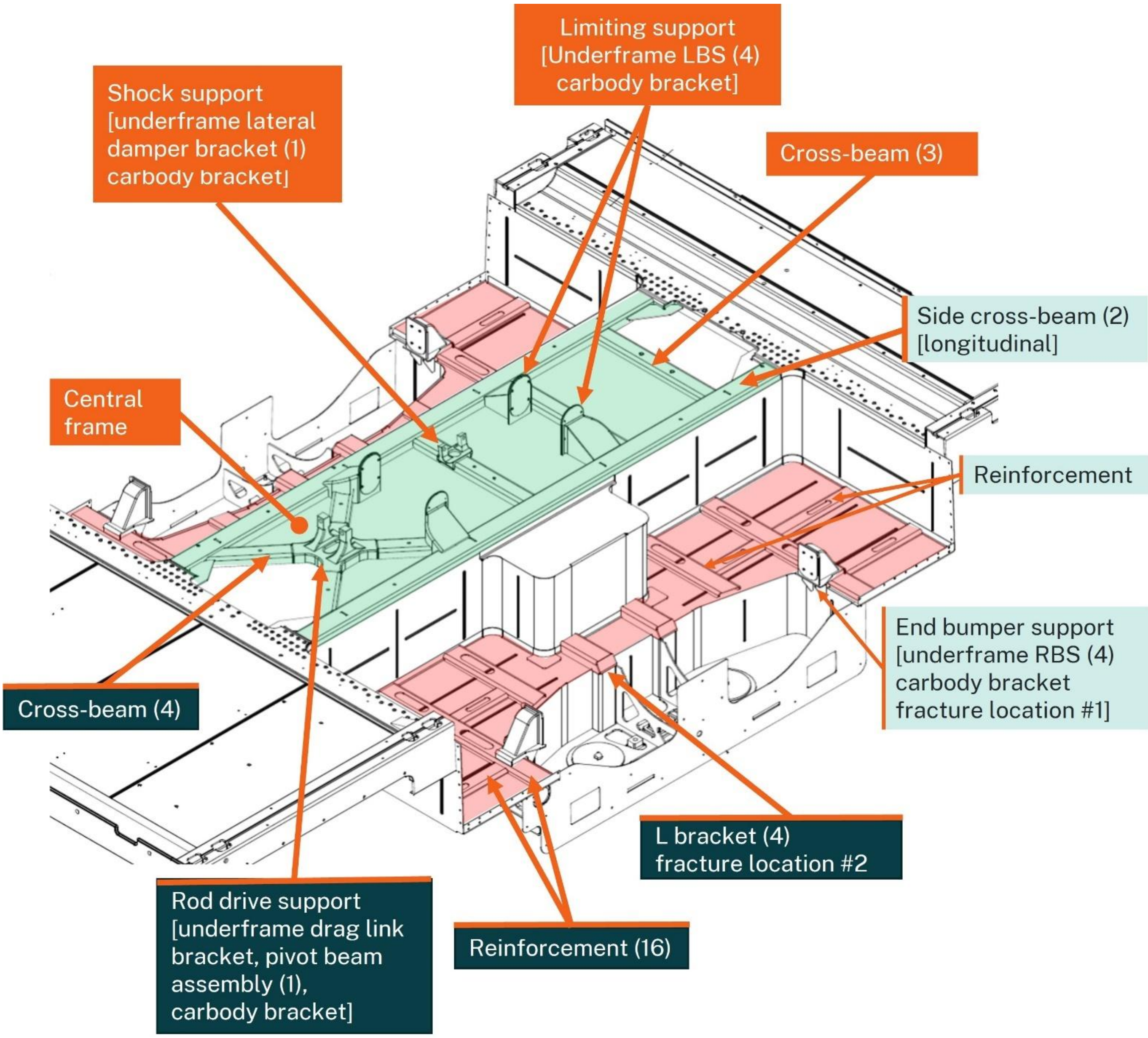
[45] Sydney Metro Tram – **Underframe – Inspect Visually** - Maintenance Manual - CAJ-00-003 Rev: 4-Feb. 2016

[46] The CAF underframe assembly drawings identified a side cross-beam as being equivalent to a longitudinal described in the TMP.

[47] The CAF underframe assembly drawings identified a cross-beam as being equivalent to a cross beam described in the TMP.

[48] Alstom considered the underframe RBS, underframe LBS, underframe drag link bracket and underframe lateral damper bracket as being equivalent to a carbody bracket described in the TMP.

Figure 21: Underframe structural components – inverted view



Inverted view of underframe noting various underframe structural components within the central frame area (green shaded region) and bogie box LHS and RHS areas (red shaded region). Structural components are labelled as per descriptions taken from CAF construction drawings. Some TMP descriptions are provided in square parentheses for the same component.
Source: CAF, annotated by OTSI

Alstom further advised that a visual inspection for fractures of components located in the red shaded bogie box region were not required. The components within that area included the underframe RBS (carbody bracket), L bracket, pneumatic sanding equipment bracket (carbody bracket - Figure 7 on page 17) and bogie box channels (reinforcements) (Figure 6 on page 16). Alstom noted that a visual inspection of those areas for fractures was not possible by a technician within the inspection pit in accordance with their interpretation of the procedure. However, a visual inspection of those areas was possible from outside of the inspection pit following the LRV side skirts being lifted. Of note was the proximity of the visible RBS fractures to the reinforcement underframe member and the pneumatic sanding equipment bracket on some of the RBS fractures observed (Figure 6 on page 16).

Detection of the bogie box fractures via visual inspection would not have been possible from inside the passenger seating area due to those locations being covered with seat mouldings. A full visual inspection of fractures in the bogie box area from underneath the LRV would also have been difficult due to the underframe being covered with thick underbody paint/sealant, in some areas noise abatement material and positioning of the bogie frame and traction motors.

h. **Underframe – Inspect Check Welding**:[49] The welding inspection check was to occur at a frequency of 2x'P3' being at 1,160,000 km. A check of the 'critical weldings' of the underframe pivot beam assembly was to occur during the inspection (Figure 20 on page 44). The inspection required removal of paint and a check of the 'critical weldings' by magnetic particle inspection. At the time of the incident, no LRVs were due to undergo the inspect check welding procedure having only travelled on average approximately 520,000 kms.

1.94 In August 2020, CAF Australia introduced an additional maintenance procedure for the Urbos 3 operating on the Canberra light rail line.[50] That procedure required the RBS clearances to be measured when a bogie was reinstalled under the carbody. In addition, the procedure also required the recording of drag link regulation shimming arrangements pre and post-bogie change. A similar documented procedure was not communicated to TfNSW or introduced into the Sydney Urbos 3 maintenance regime at that time.

Urbos 3 maintenance records

Bogie RBS clearances, free heights and bogie shimming records

1.95 The TMP did not require the recording of the RBS clearances. As such there were no records available after the factory certification testing in 2013 until post incident measurements were taken. At the time of the factory measurements the RBS clearances were recorded to be within the tolerance of 14-16 mm.

1.96 Records of the RBS free heights were not recorded during the LRV vehicle inspection and maintenance period (inclusive of the CAF Australia and Alstom maintenance periods). No RBS shimming measurements and drag link regulation shimming measurements were recorded during the Urbos 3 factory certification testing, commissioning testing and LRV inspection and maintenance period.

Bogie change out records

1.97 C module motor bogie change out records for the 5-year period leading up to the incident showed that eleven (11) of the twelve (12) LRV units had between one and 5 bogie interchanges in the period.

Rotation Bump Stop changeout records

1.98 The TMP required bogie RBS to be replaced if they were worn more than 7 mm or the RBS condition warranted changing. Between 2013 and the incident there were only records of 2 RBS being changed. Alstom advised that had the changeout rate of RBS been high that

[49] Sydney Metro Tram – **Underframe – Inspect Check** Welding – Maintenance Manual – Instruction - CAJ-01-009.

[50] CAF Australia maintained the Urbos 3 light rail vehicles operating on the Canberra Light Rail Network since that operation commenced in 2019.

would have prompted an enquiry into the potential reasons for any unusual wear or failure conditions.

Urbos 3 Operation

Monitoring of LRV speed

1.99 The speed of Urbos 3 LRVs was managed on the IWLR line through the setting of track speed limits and driver compliance with those speed limits. Urbos 3 drivers were trained to observe the speed limit signs and comply with the speed limits, with alarms being provided to the driver if speeds were exceeded. Urbos 3 C modules were fitted with data loggers to capture LRV speed, speed exceedance alarms and positional location on the network. Transdev did not have in place an automated process for monitoring and reporting Urbos 3 LRV speed compliance with the network speed boards. However, Transdev did carry out review of Urbos 3 LRV speed during driver training, driver competency assurance, regular planned driver performance reviews and unannounced speed gun radar reviews.

IWLR historic track speed review

1.100 TfNSW carried out a review of the IWLR posted track speeds since the delivery of Urbos 3 LRVs in 2013. TfNSW's review of track speed on the IWLR line followed the concerns raised by CAF from their lessons learnt in reviewing the reported cause of Urbos 3 fractures in the Birmingham fleet. Those lessons learnt identified the potential for underframe structural damage to occur through RBS contact if LRVs were not operated at the correct service speed on infrastructure with tight curves and no adjoining transition curves. TfNSW noted that some posted speed limits had increased on the IWLR network since 2013. However, changes to the speed limits were not at locations where RBS contact was likely to occur (that being track locations with tight curves and no adjoining transition curves). TfNSW also noted the track speed in the areas of track curves at or below 69 m had remained unchanged since operation of LRVs on the IWLR line.

1.101 Further details of the TfNSW posted speed review are contained in *Appendix 5: TfNSW IWLR line posted speed review 2014-2021* on page 111.

LRV time in operation and distance travelled

1.102 As at the incident date, one LRV U2123 had travelled approximately 360,000 kms with the remaining LRVs having travelled on average approximately 530,000 kms. Distances covered by the Urbos 3 fleet are tabulated in Figure 12 on page 21.

1.103 The Urbos 3 design life was specified at 30 years which equated to approximately 95,000 km/year with a total journey life of 2,850,000 km. At the time when LRV fractures were identified, the vehicles had on average travelled approximately 100,000 kms less than the distance they were expected to cover after 7 years in operation. In addition, the vehicles had only travelled approximately 14 per cent (U2123) and 19 per cent (remaining LRVs) of their 30-year design life after being in-service for that period.

Urbos 3 maintenance training and competency assurance

1.104 In 2013, CAF delivered training to CAF Australia maintenance staff covering the Urbos 3 operation and maintenance prior to their introduction into service. All training was completed by the end of April 2014. The training was planned to include corrective maintenance operation of bogies, but did not cover changing of bogies or inspection of the underframe for the presence of fractures. The documented training did not reference CAF's TMP instructions covering underframe inspections and RBS clearance measurement.

1.105 From July 2015, Alstom carried out Urbos 3 training of its technical maintenance staff. The training was advised to include an initial generic LRV induction inclusive of standard maintenance practices and systems. Training specific to Urbos 3 was then provided via a mentoring and competency assessment process with staff shown the TMP instructions and how to carry out inspections and maintenance with reference to the instructions. Technical maintenance staff were certified as competent by a maintenance supervisor once they demonstrated compliance with the TMP instructions and practices. There were no documented records detailing what was included in that specific Urbos 3 training, when it was carried out and when the final competency assessment was undertaken. However, Alstom did keep records of the training status of its technical maintenance staff which detailed if they had been assessed as competent to carry out Urbos 3 maintenance as per their process.

1.106 Transdev's Safety Management System (SMS) detailed that rail safety workers had comprehensive records of individual competence and training captured. However, Alstom could not produce those types of records and advised they were introducing a new system to capture documented training and competency assessments that would meet Transdev's SMS requirements.

IWLR track geometry design and maintenance requirements

1.107 The track geometry design for the IWLR line included a total of 7 curves of tight radii of 50 m or less. Each of those curves contained transition curve lengths[51] of 10 m or more, with a minimum of 30 mm track cant[52] applied. The speed limit for those curves were all 10 km/h with the exception of one curve that had a radii of 47 m and speed limit of 20 km/h. The Droc[53] values of all 7 tight radii curves were within (less than) the normal TfNSW mainline standard of 37 mm/s (refer to Table 2).

1.108 The track inspection and maintenance standard applied to the IWLR was derived from the RailCorp heavy rail track inspection standard TMC 203.[54] That standard specified acceptable

[51] Transition curve: A curve of uniformly varying radii used to connect straight and curved tracks or curves of different radii.

[52] Cant: Generally, the term Cant or Superelevation is used for the intended height difference in the rails (i.e. where the track is inclined in a curve).

[53] A Droc value denotes the rate of change in track cant deficiency expressed as mm/s. Track cant deficiency is the amount by which the applied track cant would have to be increased to equal the equilibrium cant in a curve. Equilibrium cant is the theoretical cant when the resultant of the train's centrifugal force at a given speed in a curve and the train's perpendicular vertical force taken across the tops of rails is balanced. In this situation there is no net lateral force on the train.

[54] TMC 203 was a Track Inspection Standard managed by TfNSW's Asset Management Branch and was adopted by ALTRAC to manage inspection and rectification of track geometry defects identified during maintenance activities. ESC 210 – Track Geometry and Stability- Engineering Standard, Version 4.8, Issued April 2013 Reconfirmed 03 July 2019 contained the related track design parameters.

track; gauge,[55] alignment,[56] rail head wear, cant and twist[57] defect limits. Related track design parameters were contained in the RailCorp standard ESC 210.

1.109 Relevant track maintenance and design standards from TMC 203 and ESC 210 are detailed in Table 2.

Table 2: RailCorp TMC 203, ESC 210 & TfNSW 2017 track standards

Parameter	Normal limit (Main line)	Maximum/absolute limit (main line)	Exceptional Limit
TMC 203 & ESC 210			
Gauge (tight) mm	12	16	
Gauge (wide) mm	26	30	
Short Twist (mm/m) @ 80 km/h	7.5	11.5	
Long Twist (mm/m) @ 80 km/h	2.85	5	
Droc (mm/s)	37	55	135
TfNSW 2017			
Short Twist (mm/m)		6.7	
Long Twist (mm/m)		4	
Droc (mm/s)	37	55	

The above gauge values identify acceptable tolerances outside of the standard track gauge measurement of 1435 mm. The above short twist and long twist values were the acceptable tolerance for the respective calculated track geometry measurements. The above TMC 203 & ESC 210 Droc values represent the various values for normal limit, maximum limit and an exceptional limit (that would require an emergency maintenance response to rectify). The above TfNSW 2017 Droc values represent the values for normal limit (to provide for the consistent experience and safety of passengers) and maximum limit (to allow for the operation of a standard interoperable LRV controlling its speed).

1.110 Considering that CAF was not supplied with the IWLR track maintenances standards in 2013, CAF advised OTSI the structural requirements for an LRV designed to standard EN 12663 assumed track conditions in accordance with the international track maintenance standard EN13848.[58] The tolerances of TMC 203/ESC 210 above were comparable with standard EN13848, with the exception of track twist limits. Those limits were similar to the track twist limits specified in the TfNSW track design and maintenance standards introduced in 2017 (see *Introduction of new TfNSW LRV standards*).

[55] Track gauge denotes the distance between the inside running (or gauge) faces of the two rails, measured between points 16 mm below the top of the rail heads.

[56] Alignment of track may be referred to as horizontal or vertical alignment. Horizontal alignment is the design horizontal alignment of track (i.e. straights, curves, etc.), vertical alignment is the design vertical alignment of track (gradients and vertical curves).

[57] Track twist denotes the variation in the cross-level between two track locations separated by a nominated distance interval. The term 'cross-level' is used for unintended height difference (i.e. due to track irregularity). Short twist denotes twist measured across a distance of 2 m. Long twist denotes twist measured across a distance of 14 m.

[58] I.S. EN13848-5-2017 – Railway applications -Track-Track geometry quality - Part 5: Geometric quality levels – Plain line, switches and crossings.

IWLR track maintenance activities and track geometry condition records

1.111 OTSI reviewed track geometry measurement data from Alstom for 2018, 2020 and 2021. That data indicated there were no areas of track with twist geometry that required immediate repairs outside of Alstom's planned program of work in accordance with TMC 203. One track twist defect was found in 2020 that required repair at that time. The remaining track defects were associated with track alignment (2021) and track gauge (2018 and 2021).

1.112 Post incident track geometry and rail wear measurements were recorded by CAF on the IWLR line between 14 May 2022 to 17 May 2022. The results of that inspection found multiple gauge and rail alignment defects against TMC 203 with no defects against track twist. Two alignment defects required action within 24 hours and one gauge defect required action within 7 days. All defects were identified in the city loop track section[59] where track speed was limited to 10 km/h for the tight curves.

1.113 The CAF ride quality testing report of July 2014, and the CAF and TfNSW on-track dynamic testing reports of April 2022 and May 2022,[60] did not identify the need to consider changes in speed arising from the track geometry condition experienced. Additional track maintenance data was not available for OTSI to review and as such any assessment made of the influence of track defects on the LRV was considered against the available data.

Introduction of new TfNSW LRV standards

1.114 In May 2017, TfNSW introduced a series of Light Rail Standards applicable to the supply of LRVs in NSW.[61] The details of those standards, in relation to the design and testing of an LRV carbody underframe, did not identify any additional or alternative standards to the standards CAF referenced in their Urbos 3 design assurances provided to TfNSW in 2013.[62,63,64]

1.115 The TfNSW light rail standard also specified track design and maintenance requirements applicable to NSW light rail network, beyond the fundamental requirements of any contract.[65] The standard's purpose was to ensure that track on TfNSW networks were designed, constructed and maintained to allow the operation of a standard interoperable LRV.

1.116 Details of the May 2017 TfNSW LRV track design and maintenance standards relevant to the investigation remained unchanged from the prior TMC 203 and ESC 210 RailCorp standard, with the exception of short and long twist absolute maintenance limits (see Table 2). TfNSW advised the purpose of the change in track twist absolute maintenance limits was to permit future interoperability of LRVs on TfNSW's LRV network. The change required a less tolerant standard of track twist applied to those lines to improve LRV ride conditions.

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59 The city loop track section was contained within the track leading into and out of Central Station bounded by the light rail crossing at Pitt Street NSW.

60 On-track dynamic testing of the Urbos 3 modified LRV design on the IWLR line took place between 6 May 2022 to 15 May 2022.

61 The introduction of LRV standards in May 2017 followed a recommendation made by TfNSW in July 2014 to identify applicable LRV design and maintenance standards for procurement of new LRVs. The recommendation was identified in the TfNSW review of the IWLR line construction and Urbos 3 procurement projects.

62 TfNSW light rail standard – General Requirements – T LR RS 00000 ST Standard Version 1.0 Issued date: 25 May 2017

63 TfNSW light rail standard – Structural Integrity and Crash Worthiness of Passenger Rolling Stock – T MU RS 01000 ST Standard Version 3.0 Issued date: 22 December 2017

64 TfNSW light rail standard – Compliance Testing Requirements – T LR RS 00000 ST Standard Version 1.0 Issued date: 25 May 2017

65 TfNSW light rail standard - Light Rail Track Requirements – T LR TR 10000 ST Standard Version 1.0 Issued date 25 May 2017

1.117 Information in the May 2017 TfNSW track design standard restated the historic mainline maximum rate of change of deficiency requirement (Droc) at 37 mm/s. The objective of that value was stated 'to provide for the consistent experience and safety of passengers.' Additional advice from TfNSW as to purpose of the Droc standard was to set a limit of lateral acceleration and jerking action, which is the rate at which an object's acceleration changes with respect to time. The purpose of the standard was not intended to relate to LRV structural integrity. A review of Droc values calculated for the track geometry on the IWLR line identified multiple locations that exceeded the 37 mm/s Droc limit. However, none of the exceedances were in tight radii curves and all were below the TfNSW exceptional limit standard of 135 mm/s (Table 2).

Urbos 3 Birmingham underframe fractures

1.118 In February 2020, CAF determined the root cause of underframe fractures in the Urbos 3 Birmingham fleet was due to contact loading between bogie and underframe RBS. CAF identified the following conditions they considered which correlated to sufficient RBS contact force to have caused the underframe fractures.

- Tight curves on the Birmingham network of 50 m or less without geometric transition curves and without appropriate track cant.
- Clearances between the bogie and carbody underframe RBS being out of tolerance. Specifically, RBS clearances that were measured at 11.1, 11.3, 12.5 and 13.1 mm, being below the minimum value of 14 mm, produced RBS undesirable contact forces on the tight curves. CAF subsequently recommended the nominal RBS clearance of 16 mm (0, -2) change to a higher value of 22 mm (0, -2). In addition, the maximum wear of the RBS was to be reduced to 2 mm instead of 7 mm with the absolute maximum RBS clearance being increased to 24 mm. The additional clearance was compatible with permissible bogie to carbody rotation restrictions. The effect of that modification was to significantly reduce the number of RBS contacts through tight curves.
- LRV speed on the tight curves operating above acceptable track geometry design parameters. For instance one curve was sign posted at 15 km/h,[66] where an acceptable speed for that curve was recommended to be reduced below 10 km/h in order to meet a Droc limit of 70 mm/s and reduce the likelihood of RBS contact loading.

Post incident LRV inspection and material testing

Urbos 3 fleet RBS clearance and free height survey results

1.119 Post incident C module RBS clearances were measured with many being below the minimum TMP tolerance of 14 mm (34 out of 96, 37 per cent). In particular, there were 6 instances of bump stop clearances below 10 mm with those values measuring at 7 mm, 8 mm and 9 mm (4 measurements at 9 mm). Records of the Sydney Urbos 3 RBS clearances measured post incident are detailed in Table 3.

[66] CAF noted that at the time of their Birmingham tender design review the track design speed at the signposted location was 10 km/h.

Table 3: Post incident Urbos 3 RBS clearance measurements

Unit	Location 1	Location 2	Location 3	Location 4	Location 9	Location 10	Location 11	Location 12
U2112	16	20	21	21	15	15	14	14
U2114	12	13	12	15	15	11	11	16
U2115	14	13	14	16	13	15	16	13
U2116	17	16	11	15	17	17	14	7
U2117	9	13	17	16	20	13	8	17
U2118	15	15	14	22	14	15	14	12
U2119	21	14	9	15	11	11	12	14
U2120	14	18	16	13	16	15	11	11
U2121	15	11	10	18	15	9	13	14
U2122	14	10	16	23	16	16	14	9
U2123	10	9	16	18	13	11	16	14
U2124	14	16	15	11	15	10	16	19

The above RBS clearances were measured in mm. The locations identified relate to each RBS position adjacent to the C1 and C2 module wheel numbers. Locations 1 to 4 are adjacent to C1 module wheel numbers 1 to 4. Locations 9 to 12 are adjacent to C2 module wheel numbers 9 to 12. The standard for RBS clearances required their measurement to be between 14 mm and 16 mm. Values recorded higher than 16 mm could indicate the diagonal RBS clearance under the minimum clearance of 14 mm. Measurements below 14 mm are shaded red.
Source: ALTRAC

1.120 The free heights of all RBS (96 in total) were measured post incident by Transdev with all RBS free heights measured to be within tolerance. Forty (40) RBS free height measurements were later provided to OTSI from Alstom with the average value measuring at 20.4 mm producing an average wear of approximately 3 mm per RBS. The lowest value recorded was 13 mm,[67] with that measurement being below the acceptable limit of 16 mm free height. The next lowest value was measured at 19 mm.

Metallurgical underframe structure assessments

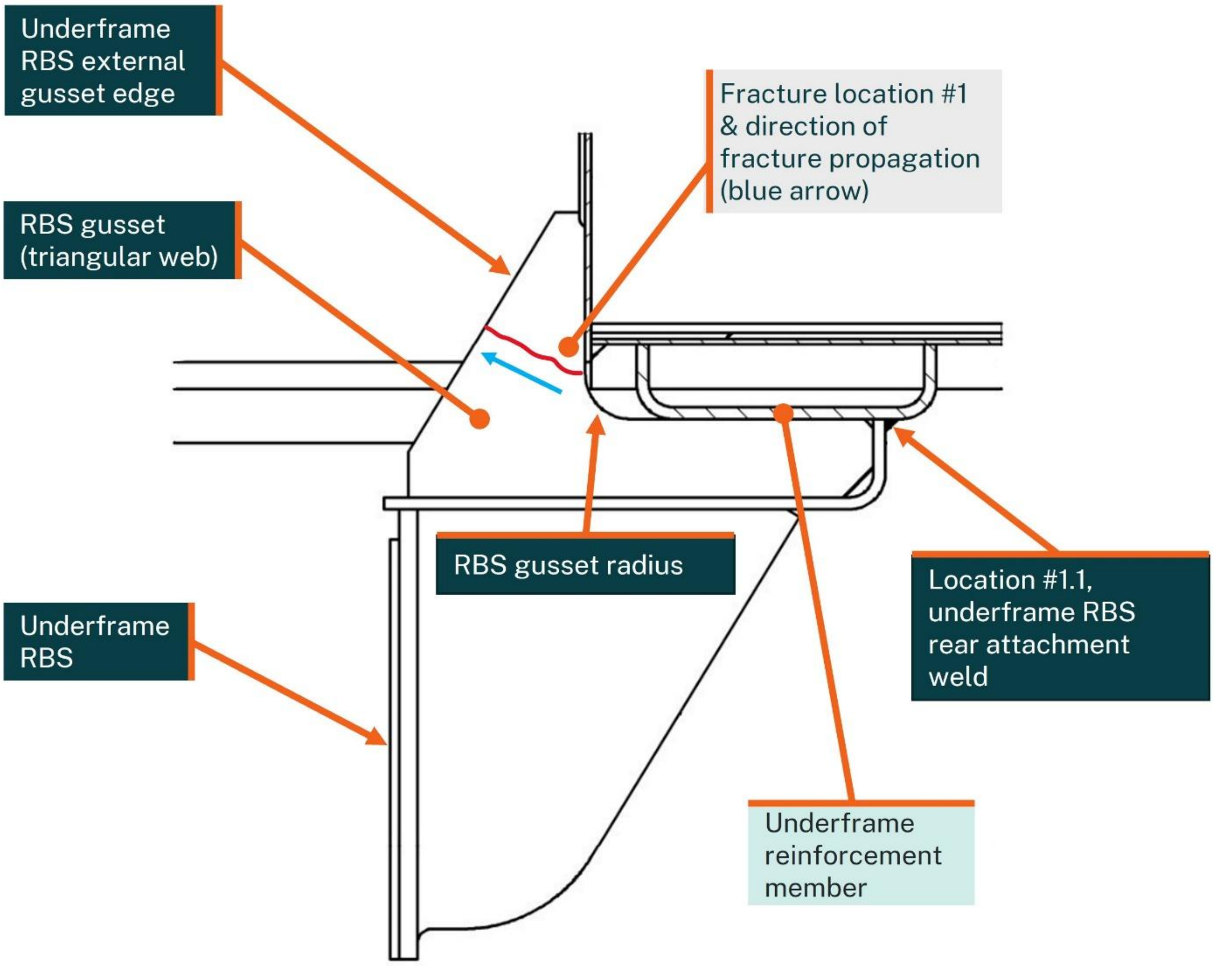
1.121 OTSI sourced a number of metallurgical analysis reports that reviewed various sections of the underframe that exhibited fractures. Those reports where required considering an assessment of where the underframe fractures initiated, and how the fractures progressed, was not possible based on a visual inspection. Results of those assessments are detailed below against the relevant underframe sections and the corresponding fracture locations #1, #2 & #3 depicted in Figure 4 on page 14.

Underframe RBS (fracture location #1)

1.122 TfNSW's metallurgical assessment report determined the underframe RBS gusset at fracture location #1 was a fatigue fracture. The direction of fracture propagation originated from the inside of the gusset radius progressing towards the external gusset edge (Figure 22).

[67] While Transdev reported that all RBS free height measurements were within tolerance, one measurement was identified as being below the TMP tolerance from the information supplied to OTSI from Alstom.

Figure 22: Fracture location #1 propagation direction in underframe RBS gusset



Side view of RBS structure depicting fracture location #1 and the direction of fracture propagation (shown as a blue arrow) in the RBS triangular gusset.
Source: CAF drawing, TfNSW metallurgical report, annotated by OTSI

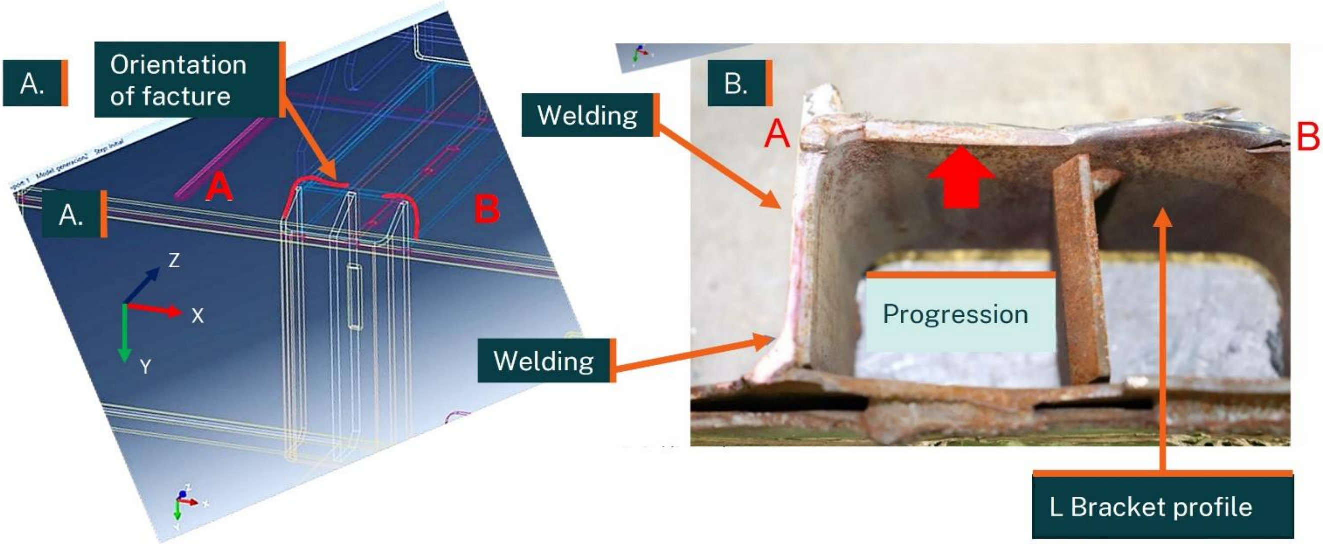
Underframe L bracket and bogie box sheeting (fracture locations #2 & #3)

1.123 A metallurgical assessment report was sourced from CAF covering the L bracket and bogie box sheeting fracture locations #2 and #3. That report detailed analysis of the L bracket and bogie box sheet structure reviewing samples representative of the fracture locations.

1.124 Findings from CAF's report detailed the following:

- The L bracket showed evidence of rupture due to mechanical fatigue, with the onset on the inner surface of the L bracket ('profile') and progression through its thickness (fracture Location #2) (Figure 23).

Figure 23: Fracture location #2 – CAF metallurgical examination of L bracket

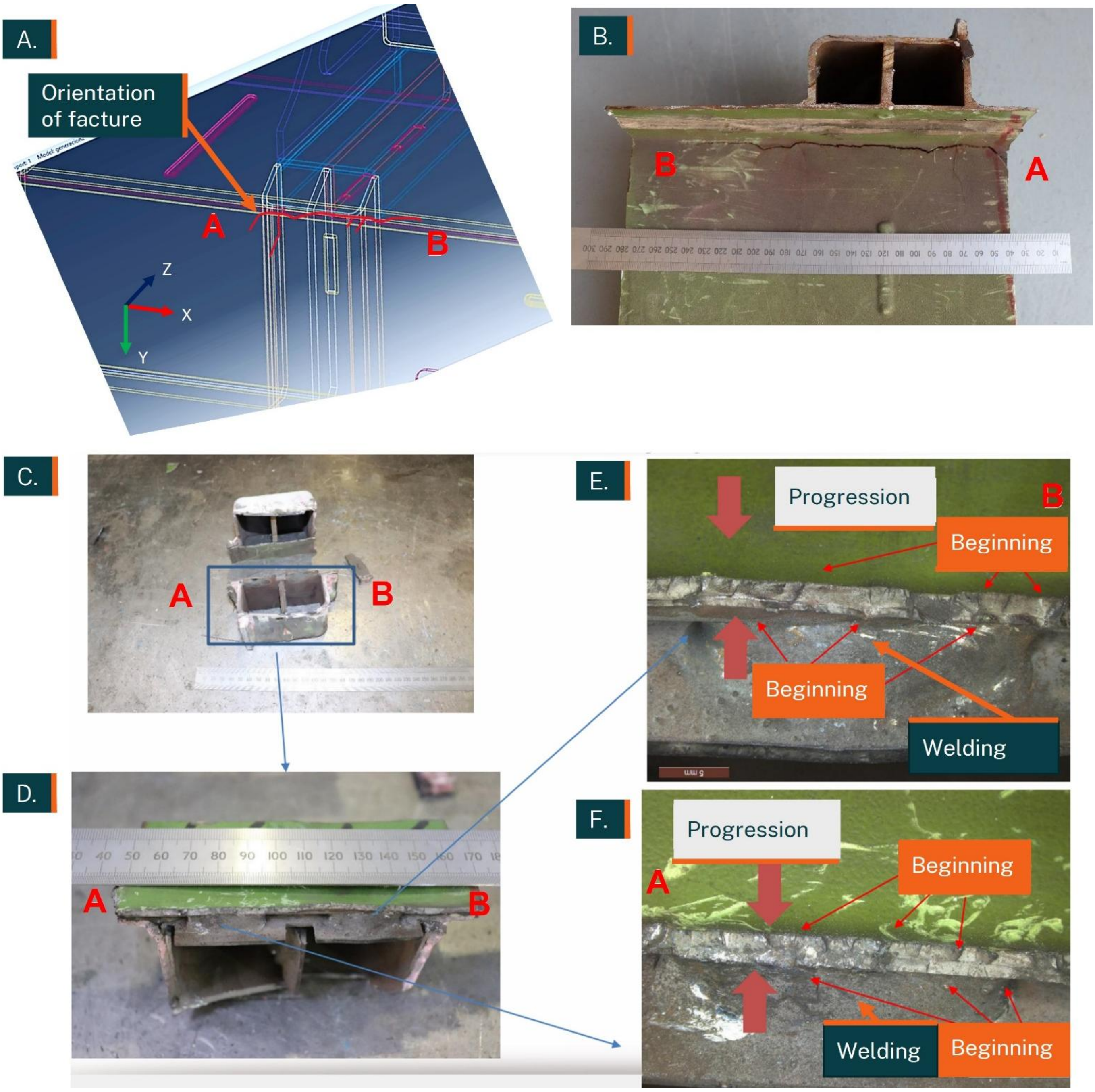


Section of L bracket (fracture location #2) removed for metallurgical examination.
Image A: Orientation of fracture examination relative to the bogie box and L bracket assembly noting reference points **A** **B** (font colour red). Image B: Top view of bogie box sheeting with reference **A** **B** (font colour red) showing orientation of the sample section relative to the position within the bogie box noting the progression direction of fatigue fracture through welding (large red arrow).
Source: CAF, annotated by OTSI

- Welding of the L bracket showed partial penetration of some of the welds (that being consistent with the manufacturing specification) and break with progression through the weld bead.
- The arrangement, advance and extension of fractures, suggested the fractures present in the L bracket (facture location #2) developed following fractures that developed in the bogie box sheeting (fracture location #3).
- The bogie box sheeting showed evidence of fatigue failure (fracture location #3) with initiation of the fractures at multiple starts located on both sides of the sheeting in the location of the welded joints and coinciding with both the welding foot and its proximity as in the welding metal (Figure 24 – E and F). CAF noted the progression was contained in a plane transverse to the thickness of the sheet.

1.125 OTSI noted from the CAF report the direction of fracture progression in a plane transverse to the bogie box sheet appeared consistent with a force acting in the Z axis (Figure 24 – A). That direction being consistent with a transverse force direction occurring through the angled "T" welding (Weld category Ref. 8, Figure 15 on page 30). The force direction also appeared consistent with bogie box sheet flexure observed in the vertical (Z axis) and horizontal (Y axis) planes (Figure 25).

Figure 24: Fracture location #3 – CAF metallurgical examination of bogie box sheeting



Section of L bracket (fracture location #2) and bogie box vertical and horizontal sheeting (fracture location #3).
Image A: Orientation of fracture examination relative to the bogie box and L bracket assembly noting reference points **A** **B**.
Image B: Top side view of bogie box sheeting with reference **A** **B** showing orientation of section relative to position within the bogie box. Graduation on scale 0.5 mm.
Image C: Section cut in two showing reference **A** **B** providing the orientation of metal section relative to the position within the bogie box detailed in Image A. Graduation on scale 0.5 mm.
Image D: Bottom section showing topside bogie box sheeting and open L bracket with vertical lap sheeting exposed and trimmed back to permit welding of L bracket into bogie box sheeting. Welding of vertical bogie box sheeting (Weld ID 47 in Figure 14 on page 29) examined in Images E and F. Graduation on scale 0.5 mm.
Image E: Macro view from reference **B** showing top side view of bogie box sheeting and examination of weld ID 47 noting progression direction (thick red arrows) of fatigue fracture on both sides of the sheeting material. That being the welded side and green painted side of the bogie box sheeting. Graduation scale 5 mm inverted.
Image F: Macro view from reference **A** showing top side view of bogie box sheeting and examination of weld ID 47 noting progression direction (thick red arrows) of fatigue fracture on both sides of the sheeting material. That being the welded side and green painted side of the bogie box sheeting.
Source: CAF, annotated by OTSI

Post incident LRV on-track dynamic testing and assessment

On-track dynamic bogie box observations

1.126 OTSI investigators attended an operational test run of LRV U2117 to observe the fractures during dynamic operation. U2117 was operated with the fractures in the bogie box area and bogie RBS area consistent with the fracture measurements that had been recorded in Figure 12 on page 21. As such the results of that test run were indicative of an LRV with underframe fractures and may not have been indicative of bogie box movement in an LRV free of underframe fractures.

1.127 During the operational run the top side bogie box area was observed to visibly move. The most notable component movement was the upper vertical bogie box sheeting and lower shelf horizontal bogie box sheeting (Figure 25). That movement appeared to coincide along the X axis referred to in Figure 25.

Figure 25: Urbos 3 original design – bogie box observations during dynamic operation

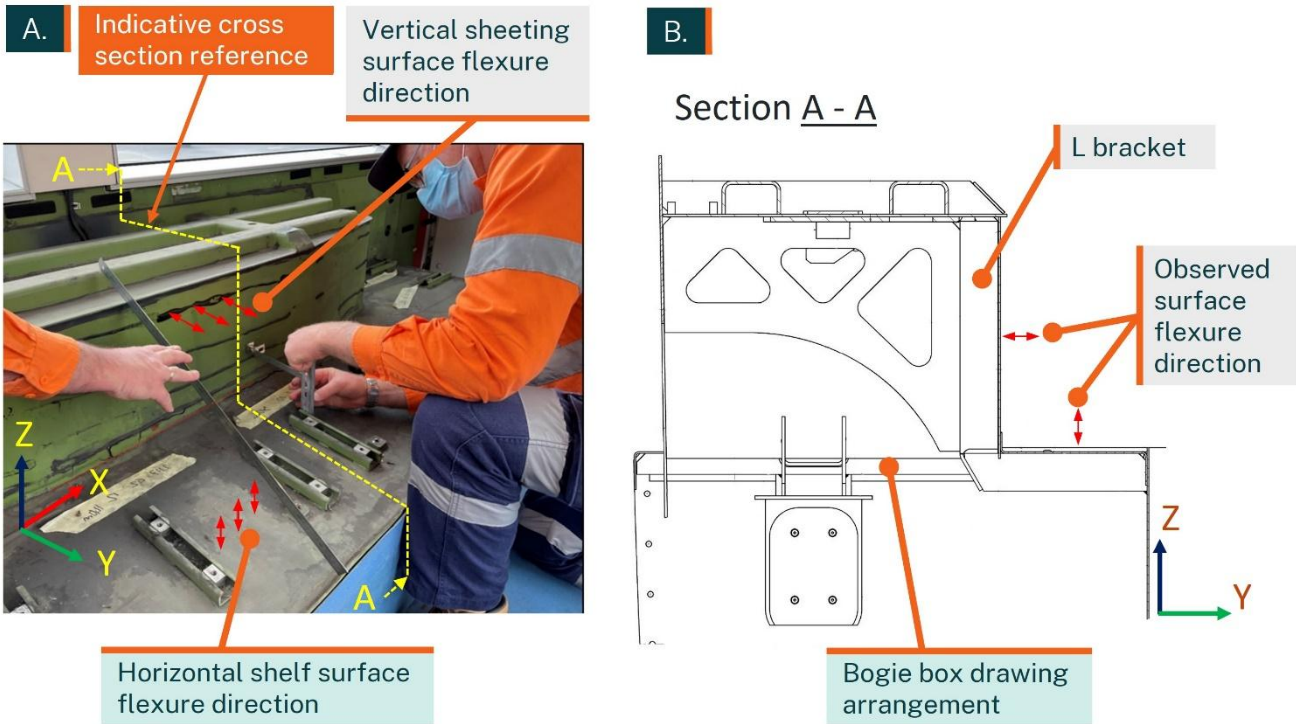


Image A: Small red arrows indicating surface flexure direction of bogie box on U2117 that was operated with fractures. Photograph mirrored vertically to align with orientation of the adjacent drawing in Image B. Image B: Small red arrows indicate movement of bogie box surface flexure. Photograph and drawing not to scale.
Source: CAF drawing. Photograph and annotation by OTSI

On-track dynamic vehicle testing

1.128 In January 2022 dynamic on-track testing of the original Sydney Urbos 3 design on the IWLR line was carried out by CAF on U2112[68] and by TfNSW on U2124.[69] Dynamic testing of the Modified Urbos 3 design was also carried out by CAF and TfNSW in April 2022 and May 2022 (see Modified Urbos 3 design on page 70). Various measurements of the LRVs were recorded including the LRV's:

- response to the track condition (in the form of acceleration levels measured on the LRV)
- underframe strain, and resulting stress, at various locations on the bogie box and RBS underframe locations
- RBS clearances measured on the C modules
- RBS contact force measured on the C module RBS underframe locations.

1.129 The test results obtained were used by CAF and TfNSW to inform their respective investigations into the Urbos 3 underframe failure and the acceptability of the Modified Urbos 3 design to meet its remaining operational life (to 30 years).

1.130 A summary of the respective testing results, relevant to OTSI's investigation are detailed below.

Urbos 3 Original design – CAF dynamic testing results – January 2022

1.131 All testing of the U2112 in January 2022 was carried out in the tare[70] weight (AW0). U2112 was tested without any remedial fracture repair. As such, the testing results were indicative of an LRV with fractures.

1.132 Three configuration types of RBS setup clearances on the C module were trialled during the CAF tests. The configuration types included:

- Configuration A – RBS setup clearances to 16 mm.
- Configuration B – RBS setup clearances to the minimum acceptable dimension of 14 mm.
- Configuration C – RBS setup clearances identified on one LRV unit measured post incident. Those dimensions ranged from 8.5 mm to 18.8 mm (8.5 mm being 5.5 mm below the minimum RBS TMP clearance).

1.133 Test results from Configuration A and B found no RBS contact, and hence no RBS contact forces applied. The tests were conducted operating on the IWLR line at the posted speed limits and operational speed restrictions.

1.134 Test results from Configuration C found RBS contact forces when the bogie RBS contacted with the underframe RBS. The RBS contact force and the frequency of that force increased as the RBS setup clearance values decreased. Contact forces were recorded against RBS setup clearances of 10.8 mm, 10.5 mm and 8.5 mm. CAF's assessment of the contact force for two RBS clearances identified lifecycle loadings of:

- 2.95 kN @ 10 million cycles for an RBS setup clearance of 8.5 mm.

[68] LRV U2112 exhibited the least number of fractures of all LRVs inspected post incident.

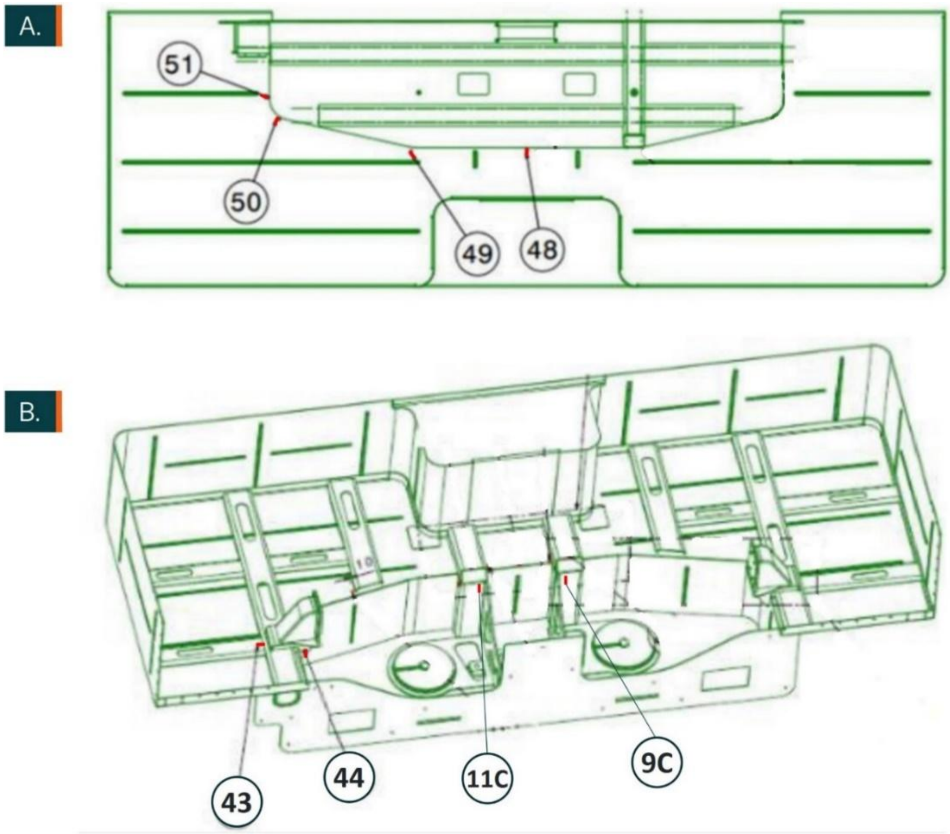
[69] LRV U2124 had the majority of fractures welded up for the purpose of assessing the LRV underframe structure in a condition relatively free of fractures.

[70] Tare weight of a light rail vehicle denotes the weight of the vehicle without any passengers on board the vehicle.

- 2.42 kN @ 10 million cycles for an RBS setup clearance of 10.5 mm.[71]

1.135 Strain gauges were positioned at strategic locations on the underframe bogie box (Figure 26). Strain values from those gauges permitted the calculation of cumulative fatigue damage results[72] for the Configuration A, B and C RBS clearance test runs. Values of the cumulative fatigue damage were assessed against the weld detail category 36 and weld detail category 80.[73] A number of the cumulative fatigue damage results were above the acceptable 30-year limit (values shown in red identifying a ratio greater than 1) (Table 4). CAF identified the highest results to be within the central frame (bogie box and RBS underframe structure). The location of those gauges that exceeded the acceptable 30-year limit were in the vicinity of fracture locations #2, #3 and #4. The exceedance values in the vicinity of fracture locations #3 and #4 were measured at all RBS clearance configurations (Configuration A, B and C). The calculative cumulative damages at each gauge were indicative of an LRV with fractures and would not be indicative of the original LRV design vehicle without fractures.

Figure 26: Original design - bogie box central frame strain gauge locations



Central frame bogie box strain gauge locations where the cumulative fatigue damage results of dynamic testing on the original Urbos 3 design was undertaken by CAF. Image A: RHS bogie box top view of strain gauge locations 48, 49, 50 and 51. Image B RHS bogie box inverted view of strain gauge locations 9C, 11C, 43 and 44. Cumulative fatigue results are referenced in Table 4 on page 60.
Source: CAF

[71] Force transmitted only in one direction with the value given with an amplitude for 10 million cycles.

[72] Cumulative fatigue damage results denote the ratio of calculated cumulative fatigue at the strain gauge location over the applicable weld detail category fatigue limit (Figure 15 on page 30 for the relevant fatigue limits). Calculated cumulative fatigue is the sum of a measured fatigue level estimated for a 30-year design life.

[73] Weld detail category 36 was used to calculate cumulative fatigue results considering force acting in the 'transverse' direction for an angled or partial penetration weld. Weld detail category 80 was used to calculate cumulative fatigue results considering force acting in the 'longitudinal' direction for an angled weld (Figure 15 on page 30).

Table 4: Original Urbos 3 design – CAF bogie box cumulative fatigue damage

OTSI fracture location	Gauge	CONFIGURATION A		CONFIGURATION B		CONFIGURATION C	
		36	*80*	*36*	*80*	*36*	*80*
#1.1	43	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
#1	44	0.15	<0.01	0.2	<0.01	0.72	0.04
#3	48	>10	1.53	>10	1.19	>10	2.04
#3	49	>10	>10	>10	>10	>10	>10
#4	50	>10	0.66	>10	0.82	>10	0.83
#4	51	6.38	0.18	7.90	0.22	8.18	0.24
#2	09C					>10	0.43
#2	11C					>10	0.62

Table identifying OTSI fracture locations and CAF gauge location numbers with reference to Figure 26. Results of cumulative fatigue damage ratios calculated for dynamic testing runs Configuration A, B and C on the original Urbos 3 design are shown. Red values identified where the ratio exceeded the cumulative 30-year fatigue assessment. Green values identified the ratio below 1 that met the cumulative 30-year fatigue assessment. Strain gauges 9C and 11C were not in place for dynamic testing of Configuration A or B.
Source: CAF, annotated by OTSI

1.136 LRV underframe and bogie acceleration levels measured during the test were recorded at values below the EN 12663 design standard limits applied as part of the original design and below the acceleration levels considered in the modified bogie box design.

Urbos 3 Original design - TfNSW dynamic testing results - January 2022

1.137 Testing of U2124 was carried out under the conditions of tare weight (AW0) and a simulated passenger loading of 5 passengers/m^2 (AW3).[74] U2124 was tested having the major structural underframe fractures welded to a provide greater level of assurance the measured stress results were indicative of the original LRV design.

1.138 One configuration (Configuration A) of RBS setup clearances was used during the TfNSW testing. All RBSs were setup to a clearance of 16 mm with no RBS contacts measured for both AW0 and AW3 test runs. TfNSW measured RBS clearances with a distance transducer during the test runs identifying 302 instances where the RBS clearance of any side reduced below 8 mm.[75] TfNSW noted that 244 (81 per cent) of those instances occurred during the AW3 test runs highlighting an increase in frequency of potential RBS contact as the LRV weight increased.

[74] Dynamic testing of Urbos 3 on the IWLR line was carried out using various passenger loading. The TfNSW (AW#) and CAF (EL #) LRV loading values applied included: AW0 (EL E) being an LRV mass in serviceable condition and without any passengers (tare), AW1 LRV mass with all seats occupied and without standing passengers, AW2 (EL 4) LRV mass at normal capacity with all seats occupied and 4 passenger/m^2 standing, AW3 LRV mass with all seats occupied and 5 passenger/m^2 standing, AW4 (EL 6) LRV mass with all seats occupied and 6 passenger/m^2 standing), AW5 LRV mass at “exceptional” capacity with all seats occupied and 8 passenger/m^2 standing.

[75] The RSB clearance of 8 mm was significant as that was the value TfNSW estimated as being the minimum value set on LRV U2112 during the CAF test program in January 2022 with that clearance resulting in multiple bogie RBS contacts with the underframe.

1.139 There were also a limited number of cycles with ranges of acceleration for the longitudinal and lateral directions at floor level which exceeded the CAF *Structural Calculation Specification* for both AW0 and AW3 load conditions.

1.140 TfNSW assessed the LRV vehicle dynamic behaviour at 8 track locations where the minimum RBS clearances were measured during testing. The results of that assessment identified the following common characteristics:

- the vehicle was entering or exiting a curve
- the vehicle was travelling in the down direction (away from Central)
- the vehicle was travelling at a low to medium speed of around 35 km/h
- the carbody load was high
- the carbody was subjected to a roll input
- the bogie was experiencing a high magnitude of yaw[76] angular acceleration (>20 deg/s^2).

1.141 OTSI notes that all IWLR line curves with a radius of 50 m or below (with the exception of the 25 m radius Up Curve 6) recorded instances during testing where the RBS clearances were 8 mm or below.

1.142 Post review of the resulting fatigue damage accumulated from in-service running identified the values to be less severe than the EN 12663 design standard constant amplitude assessment method. In addition, the peak stresses observed on all locations where strain gauges were placed of interest stayed well below the yield strength[77] of their corresponding parent material.

Urbos 3 modified design - CAF dynamic testing results – April and May 2022

1.143 Testing of the modified design was carried out on U2117 in April and May 2022 with 3 different loading configurations. U2117 was tested in the tare weight condition (AW0), loaded with an equivalent of 4 passengers/m^2 (AW2) and loaded with an equivalent of 6 passengers/m^2 (AW4). CAF dynamic testing measured acceleration levels below those applied by CAF in the modified design.

1.144 The fatigue evaluation of the stresses measured during the track test for all strain gauges located in the C2 car bogie box area resulted in satisfactory results confirming the repair effectiveness. Areas that showed fatigue damage levels exceeding the standard in testing of the original design (January 2022) at the locations where cracks appeared, no longer showed fatigue damage exceedances in the modified design (April and May 2022). Calculation of the cumulative fatigue damage results for the modified design were made considering the weld detail categories applied in that design. Those weld detail categories included 36 and 71.[78] A comparison of the CAF original and modified cumulative fatigue results grouped against the OTSI fracture locations can be referenced in Table 5 *Appendix 6: Underframe cumulative fatigue damage results* on page 114.

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[76] Yaw denotes the turning of a bogie around the vertical axis.

[77] The yield strength in steel denotes the minimum stress at which the steel will undergo permanent deformation or plastic flow without a significant increase in the load or external force.

[78] Weld detail category 71 was used to calculate cumulative fatigue results considering force acting in the 'transverse' direction for a complete welding penetration (Figure 15 on page 30).

Urbos 3 modified design - TfNSW dynamic testing results – May 2022

1.145 TfNSW's fatigue evaluation of the stresses measured during dynamic track testing showed the locations where fractures had previously occurred to have an estimated life in excess of the design life (i.e. beyond 30 years). That result was consistent for all vehicle load configurations measured (AW0, AW3 and AW4). A summary of the TfNSW cumulative fatigue damage results at the OTSI fracture locations for the original design and modified design is detailed at Table 6 in *Appendix 6: Underframe cumulative fatigue damage results* on page 114.

1.146 TfNSW also identified there were a limited number of cycles with ranges of acceleration for the longitudinal and lateral directions at floor level, as well as the vertical direction at the upper bogie box which exceeded the CAF structural calculation specification for all load conditions. However, TfNSW calculations of cumulative fatigue showed that fatigue damage accumulated from in-service running was less severe than the EN 12663 design standard constant amplitude method of assessment. That method of assessment was consistent with the standard's intended design verification process.

1.147 TfNSW assessed the number of instances where the RBS clearances measured below 8 mm during the modified design vehicle testing. That assessment identified 385 instances where the clearance of any side reduced below the minimum value set on U2112 during the CAF test program in January 2022 which was estimated to be 8 mm. TfNSW noted that 347 (90 per cent) of those instances occurred during the loaded test runs (AW3 and AW4).

TfNSW post incident design assessment of the Urbos 3 original design

1.148 In October 2022 TfNSW's specialist contractor SNC-Lavalin Rail and Transit Pty Ltd (SNC-Lavalin) completed an assessment of the Urbos 3 original design. The assessment included a FEA using CAF construction drawings and was corroborated by in-service testing measurements and vehicle dynamics modelling.[79] The design assessment reviewed the CAF original design against the EN 12663 design standard.

1.149 In summary the assessment included the following with reference to the fracture locations of Figure 4 (page 14) and the bogie box design details.

- A number of the bogie box L bracket welds, in the vicinity of fracture location #2, were assessed as weld detail category 36 (Figure 27 on page 63). The weld detail category differed to that used by CAF in their fatigue calculation assessment, with CAF using the weld detail category of 80 (see *CAF design and maintenance requirement documentation* paragraph *1.46* and *1.47*). In addition, TfNSW noted a geometric complexity of the L bracket right angle and weld construction, assessing a geometric stress concentration factor (Kt) of 2 being appropriate to apply against the level of stress at the coincidence of welds within the L bracket.

[79] TfNSW's specialist contractor SNC Lavalin applied the dynamic modelling software known as Vampire in their assessment of the Urbos 3 original design. SNC Lavalin were previously known as Interfleet Technology having contracted to TfNSW to provide specialist rolling stock advice during the LRV procurement activity.

Figure 27: Original design - L bracket welds with TfNSW assessed weld detail categories

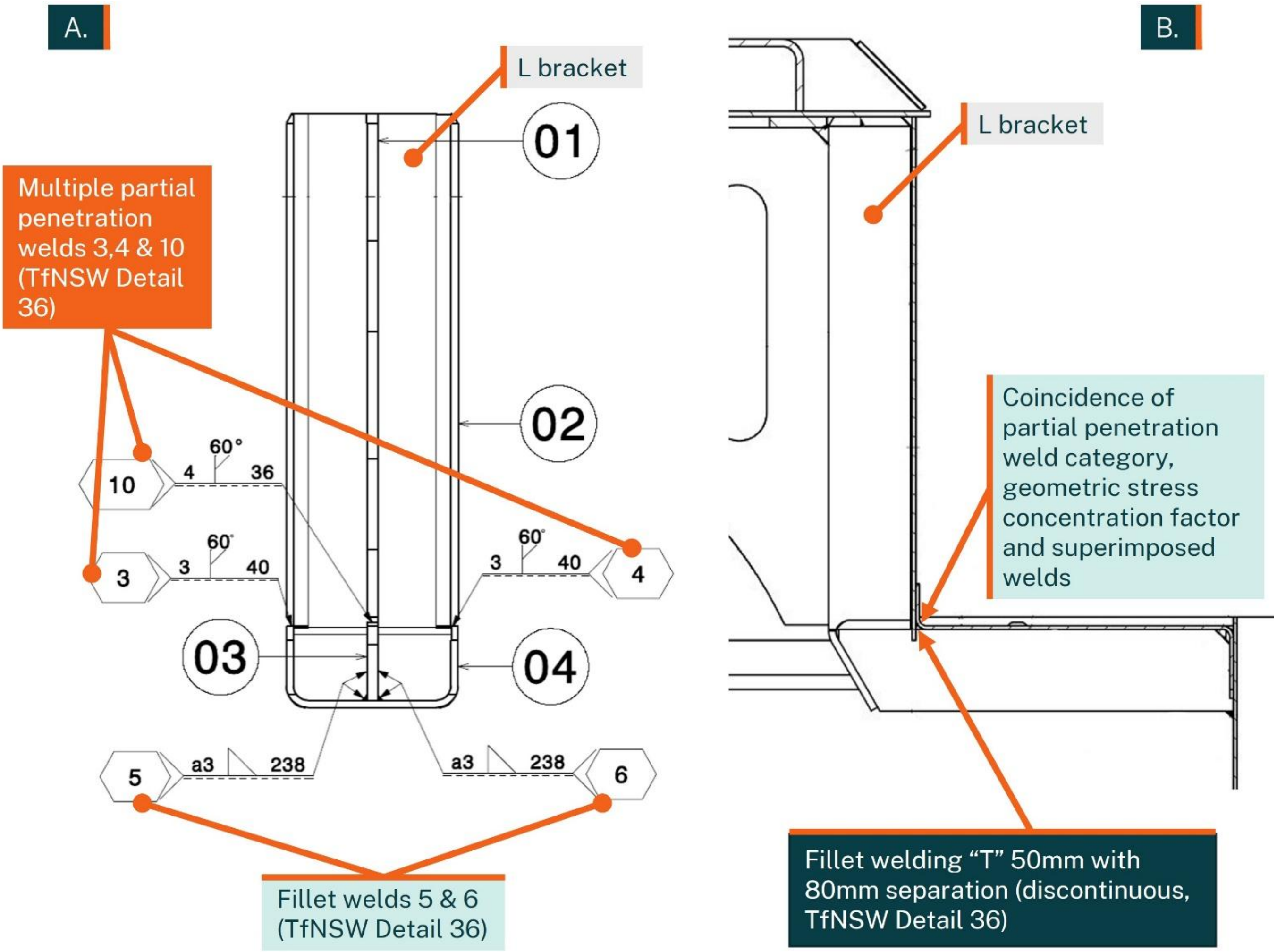

Image A details a front view L bracket assembly drawing with weld identification numbers 3, 4, 5, 6 and 10. Corresponding TfNSW weld detail categories are labelled. Image B identifies a side view assembly drawing of the L bracket and bogie box sheeting (in cross section) noting the fillet discontinuous 'T' welding and coincidence of partial penetration welds at the L bracket corner and bogie box sheeting corner construction.
Source: CAF, TfNSW weld category details annotated by OTSI

- The bogie box design at various locations were noted to not meet the design standard's vertical load case including:
  - The L bracket in the vicinity of fracture location #2 was assessed to fail at 19,000 cycles (less than 1 year of operation).
  - The bogie box upper vertical sheet to shelf lap joint in the vicinity of fracture location #3 was assessed to fail at 100,000 cycles (less than 1 year of operation).
  - The upper bogie box sheet interface with lower shelf corners in the vicinity of fracture location #4 with failure expected at 116,000 cycles (less than 1 year of operation).
- Numerous locations within the bogie box design assemblies or central frame design assembly were found non-compliant to the EN 12663 design standard when assessed against the LRV maximum operating load (AW5), dynamic transverse direction loading (AW2) and dynamic vertical direction loading (AW2). The non-compliances identified locations where the regions of high localised stress would exceed either the 'less than yield strength' or the 'no permanent deformation acceptance criteria'.

- The following RBS loading scenarios were developed for later design review including:
  - A static RBS loading of +/-20 kN per RBS was assessed as being non-compliant[80] at locations about the underframe RBS interfaces with the bogie box assemblies. Demonstration of that load assessment is presented in Figure 28.

Figure 28: TfNSW RBS FEA plot subject to 20kN RBS loading

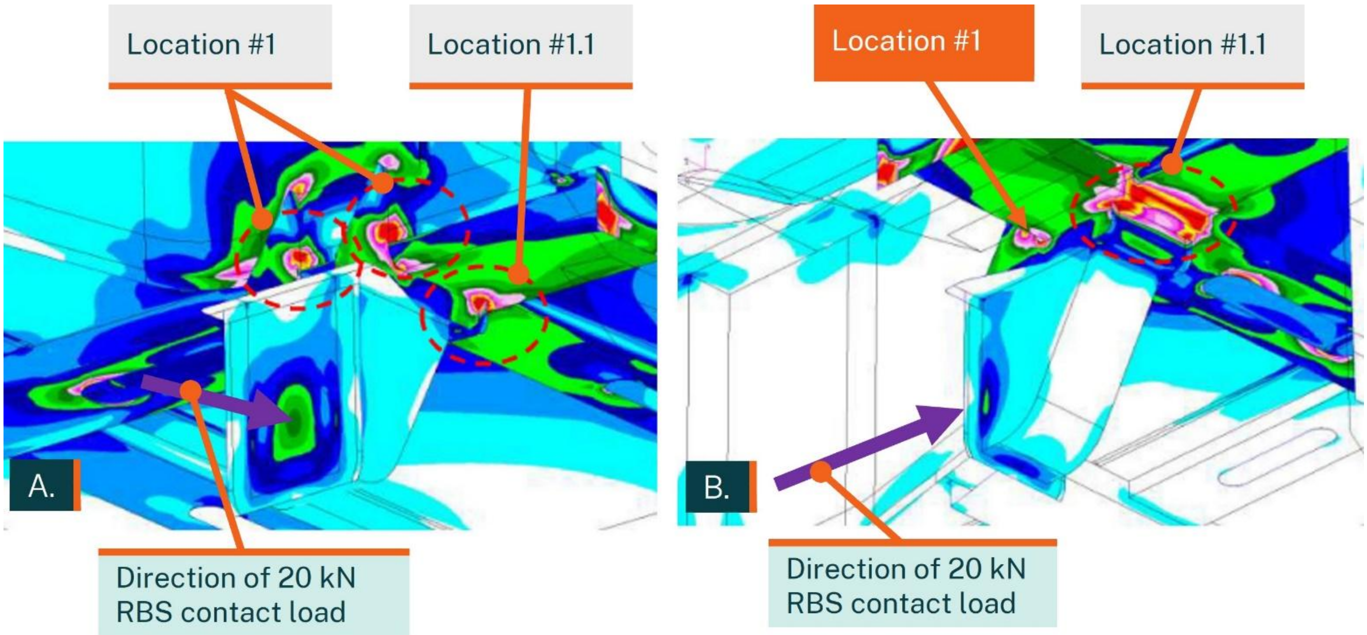

Image A: Front view of RBS loading with Location #1 and Location #1.1 non-compliant areas circled. Image B: Rear view of RBS loading with Location #1 identified and Location #1.1 circled.
Source: TfNSW, annotated by OTSI

  - A RBS fatigue loading scenario for the underframe structure at fracture location #1 was determined which meet the loading required for the EN 12663 design standard's 30-year design life. That loading scenario equated to 1.9 kN at 10^7 (10,000,000) cycles. However, the loading scenario was assessed to result in the RBS underframe structure failing the design standard at location #1.1, with the corresponding cycles to failure at 793,000 cycles (within about 2.4 years). The fatigue damage at location #1.1 was calculated to be approximately 12 times greater than at the nearby fracture location #1. The assessment noted an RBS contact loading scenario was unlikely to have to initiated fractures at location #1 as there had been no fractures identified at the nearby location #1.1 that was predicted to have developed fractures prior to location #1.
  - A constructed[81] RBS loading scenario was determined from RBS clearances set at 8 mm and a simulation[82] RBS loading scenario with RBS clearances set at 10 mm. Both loading scenarios referenced RBS contact force data and RBS clearance data from Urbos 3

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80 The non-compliance related to identification of regions of high localised stress that would exceed either the 'less than yield strength' or the 'no permanent deformation' design standard acceptance criteria.

81 The constructed RBS scenario identified a RBS force histogram derived from RBS gap measurements recorded along the IWLR line and the relationship of those measurements against known RBS contact forces measured against RBS clearances.

82 The simulated RBS scenario identified a RBS force histogram derived from application of a rolling stock dynamic software model (Vampire Pro) applied to the Urbos 3 design and measured track geometry to calculate RBS clearances and generated forces along the IWLR line.

testing carried out in January 2022 and May 2022 (see *On-track dynamic vehicle testing* on page *58*).

- Fatigue damage at the L bracket (fracture location #2) derived from LRV vertical loading was compared with fatigue damage results arising from RBS contact loading at the RBS underframe fracture location #1. The comparison referenced various loadings taken from; design fatigue loading, measured in-service testing results and all 3 RBS loading scenarios (EN 12663 design standard, constructed and simulation). Observations of the comparison detailed the following:
  - The fatigue damage from design fatigue load requirements at the L bracket location (fracture location #2) from vertical fatigue acceleration was estimated to be;
    - 79 times more damaging than a design standard endurance load (1.9 kN) applied at the RBS; or
    - 22 times more damaging than the constructed RBS variable load scenario; or
    - 7 times more damaging than the simulation RBS developed variable load scenario.
  - The fatigue damage measured from in-service testing at the L bracket location (fracture location #2) from vertical fatigue acceleration was estimated to be:
    - 44 times more damaging than an endurance load (1.9kN) applied at the RBS; or
    - 12 times more damaging than the constructed RBS variable load scenario; or
    - 4 times more damaging than the simulation RBS developed variable load scenario.
- The above results confirmed the EN 12663 design standard load scenarios were more onerous than in-service testing results for fatigue damage calculated at fracture location #2. The results also confirmed the fatigue damage calculated at fracture location #2 from vertical loading was significantly higher than at fracture location #1 based on all RBS loading scenarios.
- The TfNSW assessment also identified other locations within the bogie box that were at risk of material failure prior to the 30-year design life. Such a location included the bogie box floor panel interface to central frame assembly that had not exhibited any fractures. The assessment of those locations was qualified by the comment that it was probable secondary effects not captured within the applied methodology may have occurred, for example where load paths within the bogie box structures had changed following the onset of fractures elsewhere within those assemblies.

Additional Urbos 3 Fracture inspections - potential fracture initiation points

1.150 TfNSW carried out additional visual and non-destructive testing of potential fracture locations on the Urbos 3 underframe that were identified by their specialist contractor SNC Lavalin. Those locations were where material failure was at risk of developing prior to the 30-year design life. The locations were inclusive of the; C module bogie box sheet to floor interface corners (Figure 4 on page 14), underframe pivot beam assembly (Figure 19 - B on page 38), and an area of the R module which identified material failure well before the expected life. Results of those inspections included the following:

- The underframe inspections revealed no new fractures, weld defects or areas of concerns. In particular, the underframe welding of the C module bogie box sheeting to floor interface corners and pivot beam assembly to the underframe was of high quality.
- Overall, the fabrication of the underframe components inspected was of a very high quality.
- The R module identified area did not present with any new fracture locations.

Urbos 3 Underframe failure assessments

1.151 CAF and TfNSW carried out technical assessments of what they considered was the primary cause (root cause) of fractures within the Urbos 3 underframe. Summaries of those root cause assessments are provided below.

CAF Urbos 3 underframe root cause assessment

1.152 CAF's root cause assessment of the Urbos 3 underframe fracture occurrence detailed the fractures in the bogie boxes were produced by impacts of the bogie RBS. CAF considered the RBS impacts were likely due to excessive LRV speed into and out of curves without adjoining transition curves and incorrect maintenance tasks. Those maintenance tasks were to ensure correct clearances between the bogie RBS and underframe RBS. CAF did not identify any feedback of a design error in the original design.

1.153 Excessive LRV speed was not verified by CAF as a root cause following their analysis of the dynamic testing results carried out in January 2022. However, CAF reported it was not able to discard excessive speed as a root cause. That view was made considering CAF did not have access to historic posted track speeds on the network or actual speeds of LRV operation. The absence of that information did not permit CAF to determine if those speeds exceeded curve speed limits using a similar analysis applied in their Birmingham investigations (see *Urbos 3 Birmingham underframe fractures*). In addition, CAF reported it was not possible to verify if LRV maintenance was a root cause due to maintenance records not being shared with CAF.

1.154 CAF's assessment that the underframe fracture was caused by RBS contact was supported by its FEA review. CAF's FEA review detailed the most likely location where fractures first initiated were at critical weld crossings of the RBS structure at point 1 and then at points 2 or 3 as shown in Figure 29-A. The critical initiation point 1 being at fracture location #1 and point 3 being at location #1.1 (Figure 4 on page 14 for all fracture locations). The initiation of fractures at point 1 was noted to be consistent with a fracture progressing from that location to the outside of the RBS triangle web gusset edge as shown in Figure 22 on page 54. CAF considered that once fractures had initiated from those locations the RBS bracket itself, and other areas, became overstressed, producing further potential crack initiations in the bracket welds (Figure 29-B). The fractures were then considered to have progressed into other welds of the bogie box structure (fracture locations #2, #3, #4 and #5) as shown in Figure 29 - C and Figure 30.

Figure 29: Bogie box fracture initiation locations identified by CAF

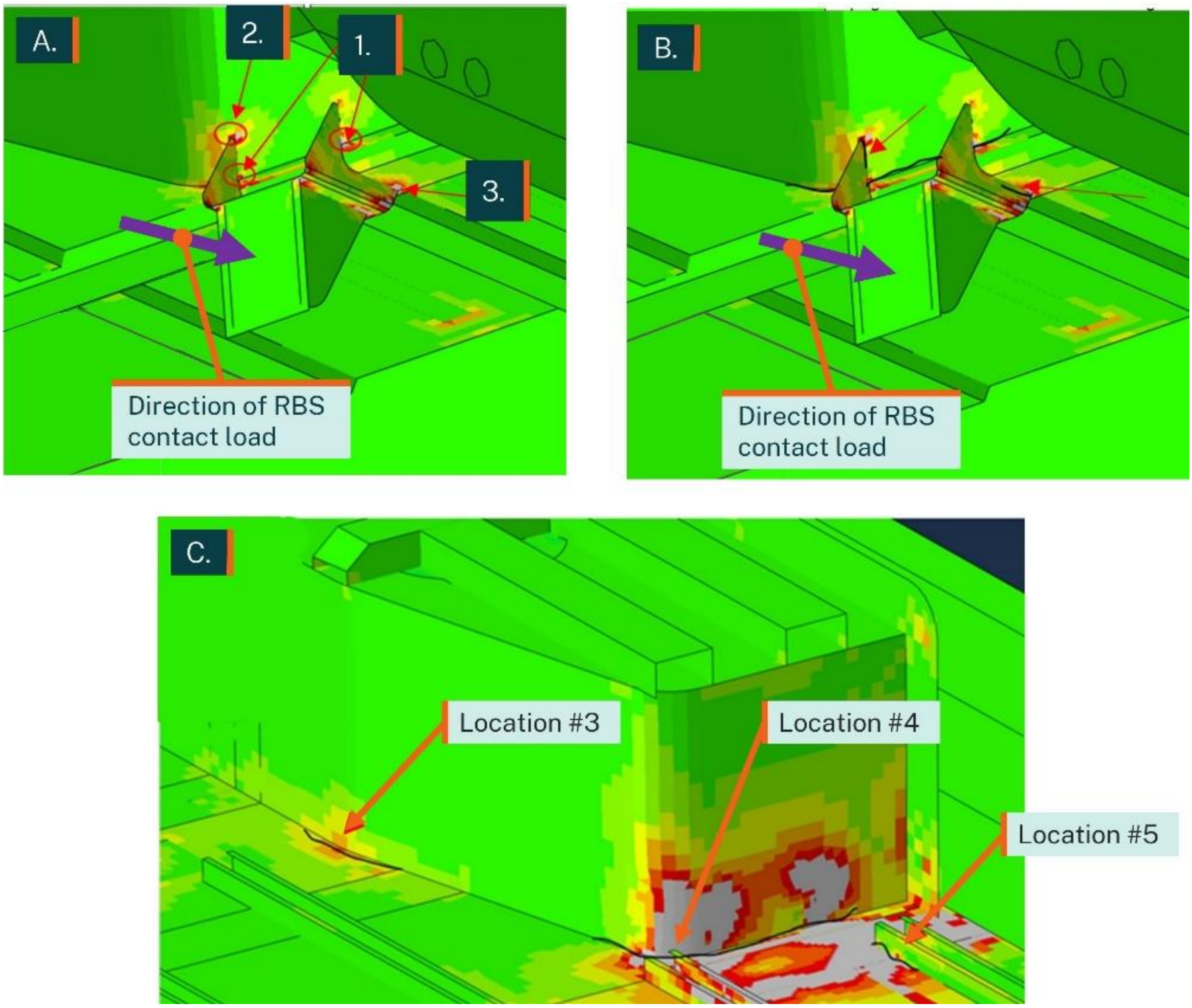
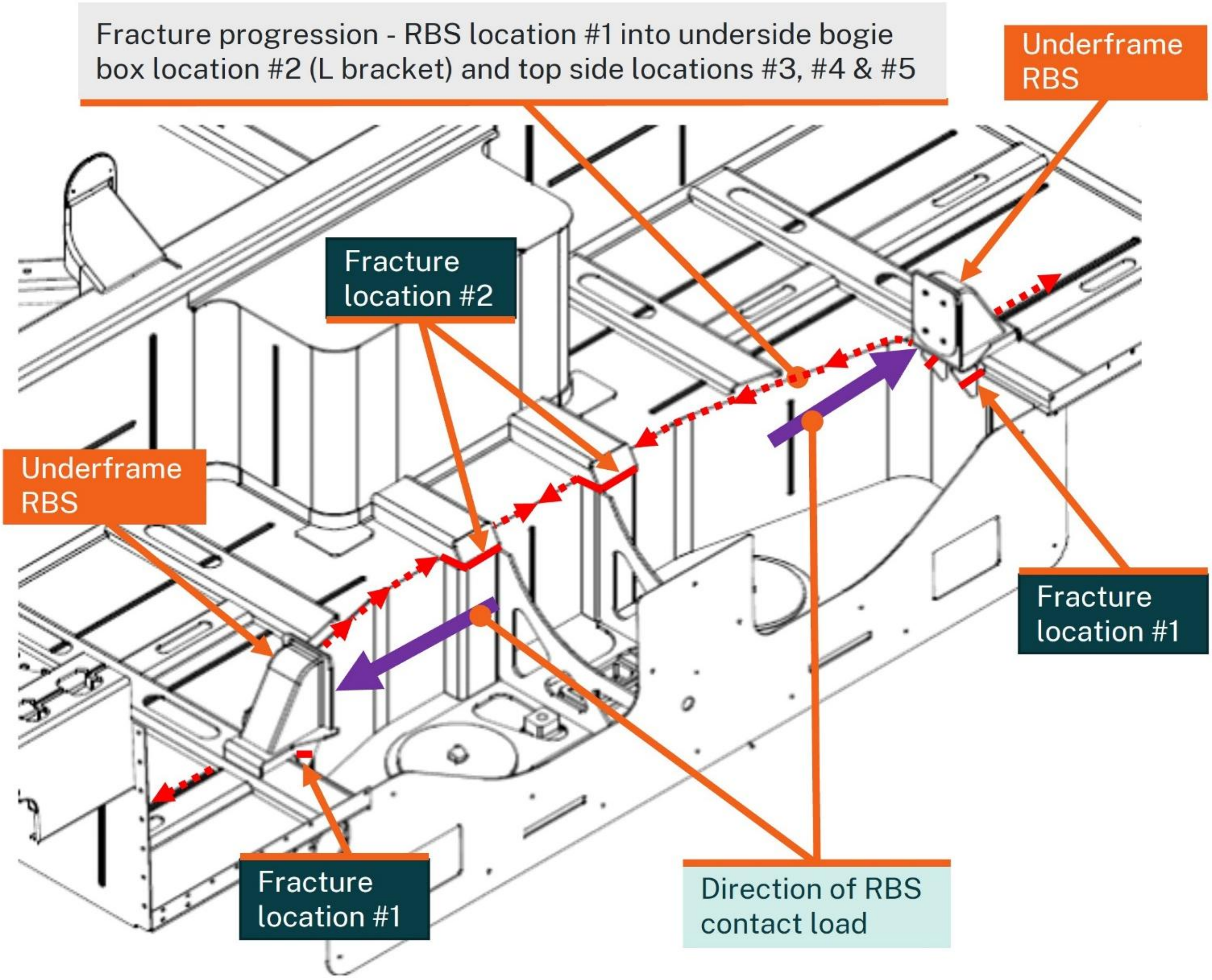


Image A: RBS contact load (purple arrow) generated fracture initiation locations starting at point 1 then likely to generate at points 2 and 3. Image B depicts fractures progressing at the RBS bracket weld locations (fracture location #1 and #1.1) and the bogie box sheeting along discontinuous fillet welds at the vertical and horizontal shelf interface. Image C depicts fractures progressing into other welds of the bogie box structure (fracture locations #3, #4 and #5).
Source: CAF, annotated by OTSI

Figure 30: CAF assessment of bogie box fracture progression from fracture location #1



Inverted view of RHS bogie box depicting RBS contact load (purple arrow) with fractures initiating at the RBS bracket fracture location #1, progressing into the bogie box with other parts of the structure becoming overstressed generating fractures in the L bracket location #2 and bogie box weld and sheeting locations #3, #4 and #5.
Source: CAF, annotated by OTSI

1.155 CAF's root cause assessment noted corrective actions taken in the modified design to eliminate possible further damage to the Urbos 3 fleet. The modified design included an increase of the robustness of the design when faced with deviations in the infrastructure and/or operation and maintenance practices. CAF concluded that there was no need to recommend modification to the operation (LRV speed) or track layout requirements different from conditions observed during the Urbos 3 dynamic testing on the IWLR line.

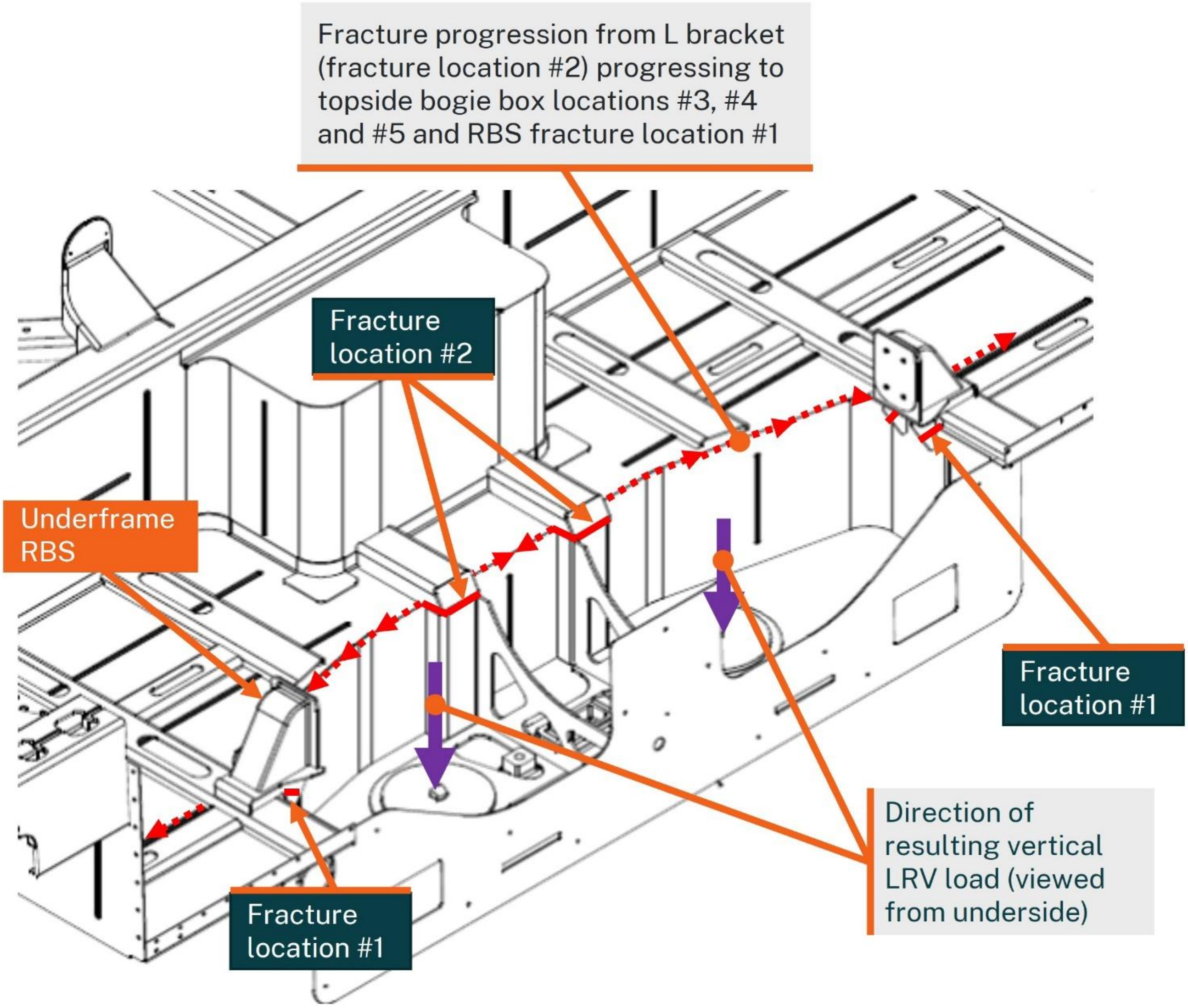
TfNSW Urbos 3 underframe root cause assessment

1.156 TfNSW's root cause assessment[83] of fractures in the underframe considered the fractures first initiated in the L brackets (fracture location #2), with other bogie box components then becoming overstressed resulting in fracturing of adjacent bogie box assembly areas (fracture

[83] TfNSW's root cause assessment was carried out by SNC Lavalin being a specialist contractor to TfNSW.

locations #3, #4, #1 and #5) (Figure 31). The root cause assessment was supported by their FEA review of the original design.

Figure 31: TfNSW assessment of bogie box fracture progression from fracture location #2



Inverted view of RHS bogie box depicting LRV vertical load (purple arrow) on underframe with fractures initiating at the L bracket (fracture location #2) and progressing into the bogie box with other parts of the structure becoming overstressed generating fractures in the bogie box locations at fracture locations #3, #4 #5 (top side of bogie box) and #1.
Source: CAF, TfNSW root cause analysis, annotated by OTSI

1.157 The initiation of fractures within the L brackets was considered to be a combination of:

- Incorrect weld details (both by defined weld assessment category and resulting geometric complexity) that were incompatible with the local stress regimes within either parent material or weld material resulting from fatigue loading regimes. TfNSW assessed a weld category of 36 for the L bracket was appropriate for its FEA. Application of that weld category, along with application of a geometric stress concentration factor (Kt) of 2, culminated in the predicted life of the L bracket being less than 1 year against the EN 12663 design standard. CAF's application of a weld category of 80 and geometric stress concentration factor for the same areas of construction considered the predicted life of the bogie box structure to meet the 30-year design life.

- Fatigue cracking propensity of the local welded joints primarily due to the vertical fatigue load case, also exacerbated by the transverse fatigue load case.

1.158 The TfNSW assessment also detailed:

- Fractures emanating from/about the L brackets was not related to forces incurred by RBS contact loading interactions (see *TfNSW post incident design assessment of the Urbos 3 original design*). The TfNSW assessment identified cumulative fatigue damage at the L bracket (fracture location #2) for vertical loading scenarios far exceeded that of the damage at the underframe RBS (fracture location #1) from RBS loading scenarios considered.
- The susceptibility of the underframe RBS structure at location #1.1 to sustain fatigue damage in any potential RBS loading scenario. The susceptibility of location #1.1 being identified in comparison to the difference in the likelihood of potential failure of the RBS underframe structure at location #1 (see *TfNSW post incident design assessment of the Urbos 3 original design*). Based on that comparison, the potential for bogie RBS contact on the underframe RBS was considered unlikely. That view was held as no fractures of the underframe RBS welding to the reinforcement member had been discovered at location #1.1.
- Simulation modelling that considered tack geometry variations, tight radius curves and LRV operation at 10 per cent over the posted speed limits. The assessment concluded the potential of fractures emanating from/about the L brackets was unlikely to be related to forces incurred by RBS interactions. The conclusion was held irrespective of the actual track geometry, tight curve speeds, or LRV operating for a period of time with below-tolerance RBS clearances. TfNSW considered the root cause of cracking in the C module bogie box assembly locations was predominantly insufficient resistance to vertical fatigue loads (primarily) and to transverse fatigue loads (albeit to a lesser degree).

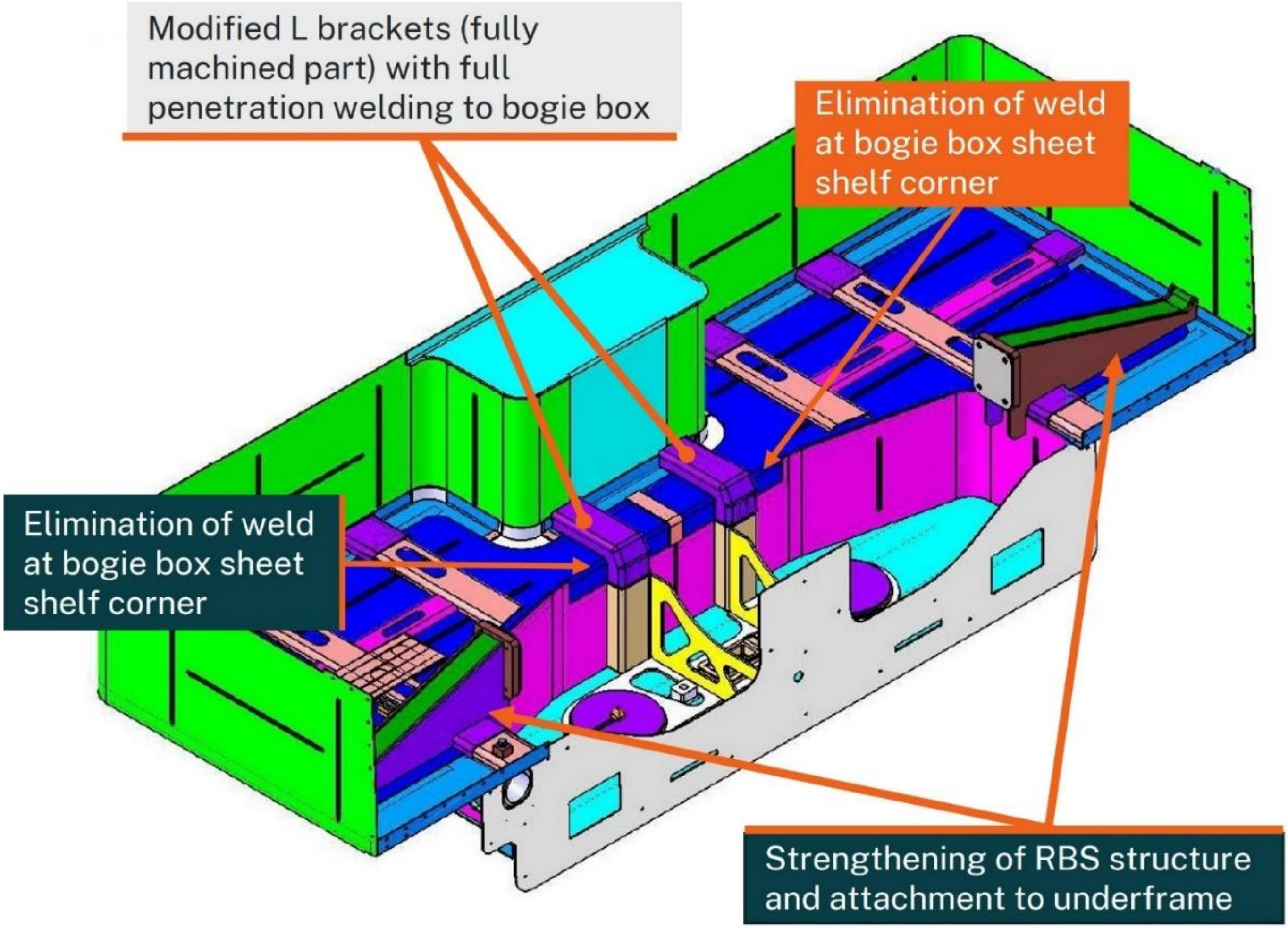
Modified Urbos 3 design

1.159 Repair of fractures in the Sydney Urbos 3 fleet was undertaken by CAF using a modified underframe design that included strengthening of the RBS structure and bogie box structure. As noted in the CAF root cause assessment, the modified design was to eliminate possible further damage to the Urbos 3 fleet including an increase of the robustness of the design when faced with deviations in the infrastructure and/or operation and maintenance practices.

1.160 In summary the modified CAF design included the following changes:

- Modification of the underframe RBS structure to be capable of sustaining a bogie RBS contact static proof load case of 100 kN and a fatigue RBS load case equivalent to 15 kN at 10^7 (10,000,000) cycles. Calculation of those load cases covered where fracture location #1 existed in the original design (Figure 32).

Figure 32: CAF modified underframe RBS and L bracket configuration – inverted view

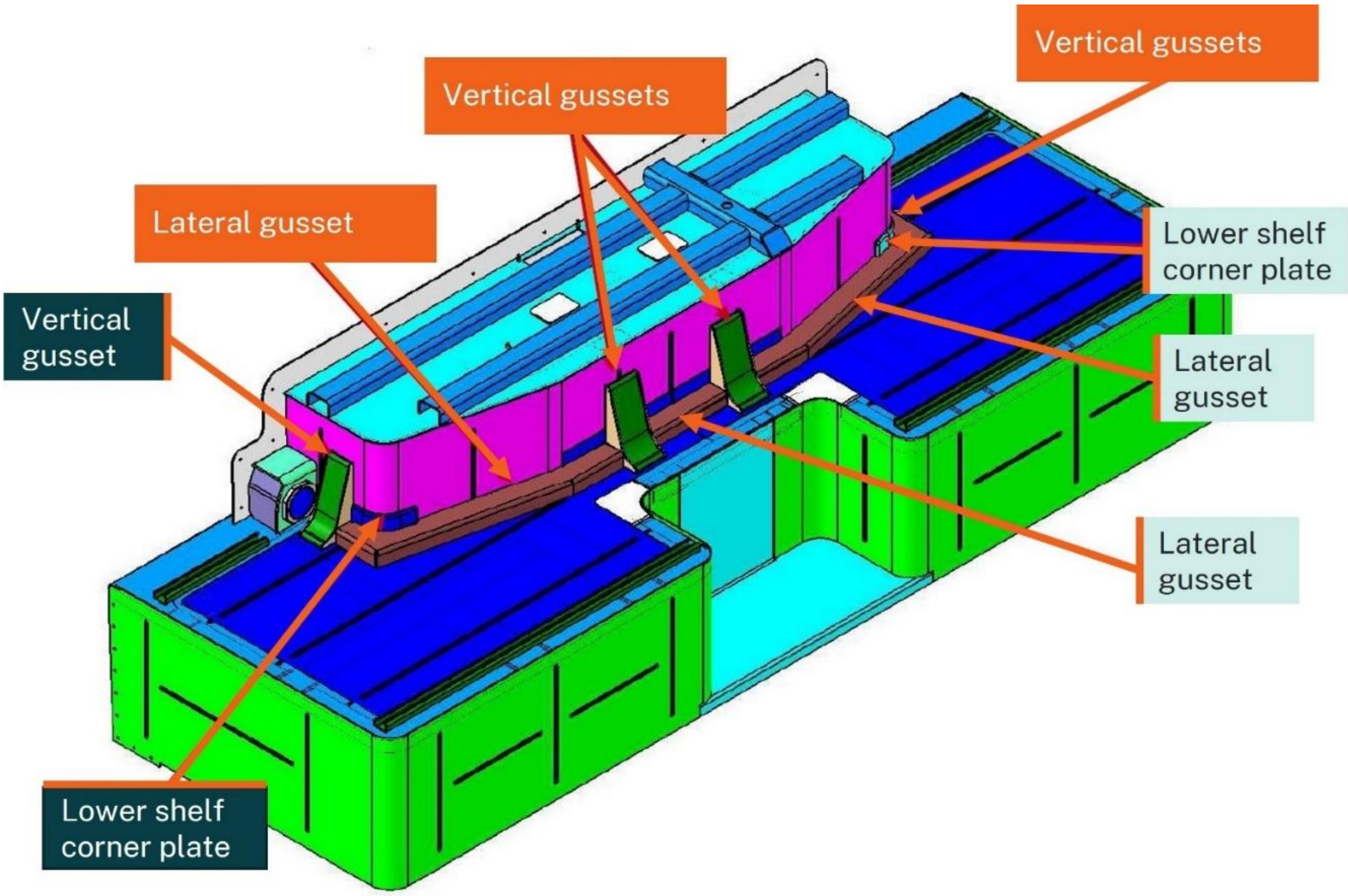


Inverted view of the RHS modified bogie box design identifying structural changes to the design including the L bracket being a fully machined component eliminating welds (fracture location #2), removal of welding at the bogie box shelf corner with a folded corner profile (fracture location #3) and strengthening of the RBS structure to include an extended mounting gusset arrangement (fracture location #1).
Source: CAF, annotated by OTSI

- Strengthening of the bogie box structure at key locations (Figure 32 and Figure 33) including:
    - Elimination of welding to construct the L bracket in the vicinity of where fracture location #2 existed in the original design, with the L bracket being constructed from a fully machined piece of steel.
    - Elimination of a section of welding between the upper to lower bogie box shelf corner in the vicinity of the L bracket connection to the bogie box sheeting. The elimination of that weld was at fracture location #3.
    - Strengthening of the upper bogie box sheet interface with the lower shelf corner plates, where fracture location #4 existed, through the addition of a fully machined corner plate welded into the corner.
    - Strengthening of the upper to lower bogie box shelf arrangement with an additional lateral gusset along the upper bogie box sheet interface with the lower shelf. That gusset covered both fracture location #3 and location #4.

- Additional strengthening of the upper to lower bogie box shelf arrangement with 4 vertical gussets covering a section of where fracture location #3 existed and in the vicinity of where fracture location #4 existed.
- Construction of the modified sections of the bogie box structure with stronger continuous welding as opposed to the original design welded joints that were discontinuous welding.

Figure 33: CAF modified bogie box configuration



Top view of the RHS modified bogie box design identifying structural changes to the design including the addition of multiple lateral gussets (fracture locations #3, #4 and #5) and strengthening corner plates (fracture location #4).
Source: CAF, annotated by OTSI

1.161 TfNSW noted the CAF modified design aimed to repair cracks found within the bogie box assembles and provide localised structural reinforcement in those locations where fracture initiation was deemed by CAF to occur. The modifications identified include two (2) key changes to the original design detail. Those being:

- A larger structural attachment was provided for the LRV RBS to further distribute the load.
- Additional brackets and reinforcements provided along the seam between the upper and lower portions of the bogie box to further distributed the load experienced in the bogie box L brackets.

1.162 TfNSW also noted the cumulative fatigue damage calculated for the modified design, around areas with known cracking issues in the original design, were found to have an estimated life in excess of the 30-year EN 12663 design standard requirement.

Part 2 — Analysis

Introduction

2.1 OTSI's investigation sought to determine the cause of the incident and any recommendations that could be made for the purpose of transport safety. OTSI's investigation has not sought to apportion blame or determine any liability for the incident. The OTSI investigation subsequently focussed on reviewing how the incident occurred, and the safety controls identified and applied by the relevant organisations to mitigate against fracturing of the Urbos 3 underframe. The investigation also included a review of what action was taken by the relevant organisations to manage the risk of underframe fractures following the knowledge of their existence before a safety incident arose.

2.2 To achieve that scope, the investigation considered a number of potential hypotheses. The following analysis contains details of those hypotheses covering the Urbos 3 procurement, design, commissioning, operation and maintenance. For the purpose of reporting the analysis the physical mechanisms of how the underframe fractures may have occurred are presented first. The second part of the analysis then details those potential factors that were noted to exist and which were likely to increase the risk of underframe fractures occurring. The last part of the analysis reviews what action was taken to mitigate the risk of Urbos 3 fractures following their detection.

Review of Urbos 3 fracture mechanisms

2.3 The investigation considered 3 main hypotheses to explain how underframe fractures may have initiated within the Sydney Urbos 3 LRVs. Consideration was also given to the possibility that the 3 hypotheses existed in combination, or if not proven, may have existed as factors that could have increased the risk of fractures developing in the underframe. The 3 main hypotheses included the underframe fractures being initiated through:

- **Anticipated operational design loading** placed on the LRV with the underframe design not being able to withstand that loading.
- **Bogie rotation bump stop (RBS) loading** of the underframe that was not considered in the original design.
- **Inherent structural welding defects** of the underframe that may have reduced the underframe's strength to cope with the LRV operational loading.

Operational loads

2.4 Analysis of the Urbos 3 design in the vicinity of where fractures had been identified was considered against multiple LRV fatigue loading scenarios. Those LRV loading scenarios included; LRV design requirement loadings (EN 12663 design standard), operational loading measured during dynamic testing on the IWLR line and simulated loading based the LRV structural design and dynamic test data.

Original design loading

2.5 CAF's FEA assessment of the bogie box construction carried out in 2013 detailed the structure complied with the mandated vertical, transverse and longitudinal fatigue loads specified with the EN 12663 design standard. CAF's FEA assessment of the fatigue vertical load case identified the maximum principal stress in the C1 carbody welded material at 51 N/mm^2 located within the vicinity of the bogie box sheeting at weld ID 47 (Figure 13 – B on page 28 and Figure 14 - B, fracture location #3 on page 29). An allowable fatigue limit of 51 N/mm^2 was used by CAF to assess the fatigue life at the maximum principal stress location. CAF's selection of the weld detail category 80 for the location was reliant on the assessment of stress acting in the longitudinal direction (Figure 15 – Ref 7 on page 30). A review of the CAF static strain gauge testing (see paragraphs 1.82 to 1.85 on page 40) identified strain gauges were not placed in close proximity to the maximum (major) principal stress in the welded material identified in their FEA assessment as shown in Figure 13 (page 28). An opportunity at that point existed for CAF to validate their assessment of the estimated maximum stress in welded material in terms of the magnitude and direction. A rosette stain gauge[84] placed at such a location may have provided further insight into the direction and magnitude of stress at the location in proximity to weld ID 47 (fracture location #3) and weld IDs 3 & 4 (fracture location #2).

2.6 The location of major principal stress in the bogie box was also in close proximity to the L bracket (fracture location #2). CAF assessed the L bracket structure welds for that location to be weld detail category 100 with the direction of stress in the longitudinal. The weld detail category 100 had a corresponding fatigue limit of 64 N/mm^2. The direction of stress for that location was selected on the basis of force being parallel to the weld run as shown in the CAF FEA stress direction plot (Figure 16 on page 31). The maximum stress in the L bracket weld was calculated at 57.7 N/mm^2 providing an estimated fatigue life of approximately 43 years. However, if the maximum stress was assessed against a weld category of 36 for stress acting in the transverse direction, a mean design life of less than two (2) years would result.

2.7 The TfNSW FEA assessment carried out in 2022 of bogie box fatigue life against the design load requirements assessed several locations within the bogie box structure to be non-compliant with the EN 12663 design standard. In particular, the TfNSW assessment identified the bogie box sheeting and L bracket fabrication welding (fracture locations #2 & #3 respectively) to have a fatigue assessment against a weld detail category 36. Assessment of the L bracket and bogie box sheeting arrangement at that location using the weld category 36 resulted in those locations not complying with the design standard. The TfNSW assessment estimated a mean service life of less than one (1) year for both locations.

2.8 The main difference between CAF and TfNSW's assessment of fatigue life against the EN 12663 design standard (without consideration of any comparison between geometric stress concentration factors Kt) was selection of the applicable weld detail category. By way of example, an assessment of the fatigue life using the value of maximum principal stress in welded material of the bogie box at 51 N/mm^2 against a weld detail category of 36 (appropriate for a direction of stress acting in the transverse direction) would result in a forecasted mean service life of approximately two (2) years. Hence, the sensitivity of calculating an estimated fatigue life at fracture location #3 between the two weld detail categories of 80 and 36 could be approximately 28 years. A similar observation could be made

[84] A rosette strain gauge is an arrangement of multiple strain gauges positioned closely together to measure strain in different directions on a component.

when calculating the fatigue life at fracture location #2 between the two weld detail categories of 100 and 36.

2.9 TfNSW's assessment of fatigue loading identified other bogie box locations that were at risk of material failure prior to the 30-year design life. Such a location was the bogie box floor panel interface with the central frame assembly that had not exhibited any fractures. The assessment of those locations was qualified by the comment that it was probable secondary effects not captured within the applied methodology may have occurred, for example where load paths within the bogie box structures had changed following the onset of cracking elsewhere within those assemblies.

RBS loading not considered in the original design

2.10 CAF's original Urbos 3 design of 2013 did not anticipate repetitive RBS underframe contact, with post incident advice from CAF detailing that contact could negatively affect the carbody shell. Post incident measurements of the RBS clearances on the Sydney Urbos 3 fleet identified the potential that RBS clearances could have been reduced (become out of tolerance) on a number of vehicles during their operational life. A review of maintenance records identified numerous instances where bogies were interchanged (see *Bogie change out records*) without there being any direct control over the setting of RBS clearances. The extent of bogie interchanges further supported the possibility of reduced RBS clearances impacting on the Urbos 3 operation. Therefore, the potential for RBS loading to occur due to RBS clearances not being maintained to the required TMP tolerances was analysed. The potential locations where that type of loading may have occurred on the IWLR line was also analysed.

2.11 CAF and TfNSW dynamic testing of LRVs on the network in January 2022 and May 2022, established that bogie RBS contact with the underframe would not occur if the RBS clearances were maintained to the required TMP tolerance of 14 mm to 16 mm. CAF and TfNSW also established that RBS contact with the underframe was most likely to occur on the network with tight radii curves.

2.12 CAF identified a potential RBS loading scenario on the IWLR line of 2.95 kN loading at 10^7 (10,000,000) cycles with an RBS clearance of 8.5 mm (Configuration C) from their dynamic on-track dynamic testing. CAF calculated cumulative fatigue damage results were noted to increase at location #1 for testing with RBS clearances at 8.5mm (see gauge 44 in Table 4 on page 60).

2.13 TfNSW reviewed the RBS structure against the EN 12663 design standard for fatigue loading using an FEA model. That review identified an RBS loading limit to meet the 30-year design life at the weld in the vicinity of fracture location #1. The acceptable loading scenario for the weld equated to 1.9 kN loading at 10^7 cycles. However, that loading scenario was assessed to result in the RBS underframe structure failing the design standard at the nearby location #1.1 within about 2.4 years. Hence location #1.1 was identified by TfNSW as being the most likely point of failure when subjected to any RBS loading scenario.

2.14 TfNSW also reviewed all Urbos 3 dynamic testing results (inclusive of CAF's results) and identified multiple RBS loading scenarios based on measured RBS loads and simulation RBS loading values. Some of the RBS loading values and scenarios included an assessment of a 2.95 kN loading at 10^7 cycles. That RBS loading scenario approximated failure at fracture location #1 to occur in about 6 years. However, TfNSW noted that no fractures were identified at location #1.1 where they would have expected fractures to first initiate based on their FEA assessment.

Operational loads observed during on-track dynamic testing

2.15 Dynamic on-track testing of the Urbos 3 was carried out by CAF and TfNSW in January 2022 and May 2022. A summary of those tests is detailed in *On-track dynamic vehicle testing* on page 58.

2.16 CAF and TfNSW analysis of the operational conditions experienced during that testing recognised the acceleration levels acting on the LRV were below those applied within the EN 12663 design standard. The observation acknowledged the resulting operational loads applied to the LRV were also below the loads mandated by the design standard. The outcome of that observation was likely to mean the operational life of the LRV design would last longer than any forecasted mean service life calculated by the design standard. The observation would also rely on the; LRV structure being designed to meet the design standard loadings, consistent application of a quality standard to the LRV manufacture, and operational conditions (track condition and LRV speed management) remaining like those measured during on-track testing. The observation also indicated that track geometric conditions at the time of testing were not of the magnitude to cause any undue vehicle loading not already considered. Likewise, there was no undue vehicle fatigue loading concerns (based on measured vehicle acceleration levels) highlighted by CAF in the original vehicle performance tests carried out in 2014 during the Urbos 3 commissioning.

2.17 Actual track geometry, related maintenance data and actual LRV speed data was not available to assess if the track condition or potential LRV overspeed between 2014 and 2021 was likely to impact on LRV fatigue loading during that period. While some track maintenance geometric data was provided to the investigation (see paragraphs 1.111- 1.112 on page 51), the extent of those defects were either; permitted for repair under the track maintenance standard or they did not result in LRV acceleration levels (as measured during vehicle load testing in May 2022) to warrant any change in operational speed on the IWLR line.

Review of underframe fracture locations against potential RBS loading scenarios

2.18 The location of fractures detected in the Sydney Urbos 3 fleet are detailed in *Urbos 3 Fleet fracture location data* on page 20. Analysis of the fracture locations as to where fractures may have first initiated in the underframe was assessed based on the fracture data. That assessment also considered the different views held by CAF[85] and TfNSW[86] as to where the underframe fractures first initiated. The following observations were drawn from the analysis.

a) CAF's theory of where fractures first initiated was predicated on a two key conditions. These conditions being:

i. **Bogie RBS contact with the underframe due to RBS clearances being set outside the TMP minimum tolerance.** Testing on the IWLR line revealed no RBS contact would occur if RBS clearances were set in accordance with the TMP. However, RBS clearances of the Sydney Urbos 3 fleet measured post incident identified 37 per cent of fleet clearance below the TMP tolerance (see *Urbos 3 fleet RBS clearance and free height survey* results on page 52). Test results also identified that

[85] Refer to *CAF Urbos 3 underframe root cause assessment* on page 66.

[86] Refer to *TfNSW Urbos 3 underframe root cause assessment* on page 68.

RBS clearances needed to fall below 10 mm before the recorded RBS contact force was measured to a level considered sufficient to result in reportable cumulative fatigue damage (see *Urbos 3 Original design – CAF dynamic testing results – January 2022* on page 58). No records of RBS clearances were documented after the Urbos 3 commenced operation in 2014. As such it was not possible to determine the duration or extent of how far RBS clearances were potentially outside the TMP during LRV operations.

ii. **Bogie RBS contact with the underframe would result in fractures first initiating at fracture location #1 and then extending into the RBS attachment welding to the underframe reinforcement member (including at location #1.1)**. The fractures were then predicted to progress into the other observed fracture locations #2, #3, #4 and #5 as those areas in the central frame became overstressed due to the RBS failure.

b) The fact that fractures at the RBS (location #1) were only found in 35 per cent of LRVs did not support CAF's view that all underframe fractures resulted from RBS contact (see *Urbos 3 Fleet fracture location data* and Figure 12 on page 20). For instance, U2112 was identified with the least number of fractures, with its C1 module at wheel 2 (W2) side bogie box exhibiting no RBS underframe fractures at Location #1 or top side bogie box fractures (locations #3, #4 or #5), yet all bogie boxes exhibited L bracket fractures at location #2. A similar observation was made for the C1 module W2 bogie box side of U2114.

c) TfNSW's theory of where fractures first initiated in the underframe was predicated on the bogie box being of insufficient strength to withstand vertical, and to a lesser extent lateral operational fatigue loads experienced during the LRV's service life. In particular, the TfNSW theory identified the L brackets (fracture location #2) to be the most likely location where fractures first initiated in the underframe. The fact that 100 per cent of the L brackets (fracture location #2) were identified with fractures was consistent with the theory of fractures initiating from that location.

d) TfNSW's FEA assessment of the RBS structure against the EN 12663 design standard noted that RBS fractures were likely to first initiate at location #1.1 in the event RBS loading was to occur. However, no fractures were identified at that location. That fact opposed the CAF hypotheses that RBS contact forces of any magnitude or frequency would result in fractures occurring at fracture location #1 by the time they were discovered in 2021. The TfNSW assessment also supported the view that RBS set-up clearances found to be below the CAF TMP standard had not resulted in sufficient RBS loading to have caused fractures at location #1.

e) The above analysis indicated that RBS contact loading was not likely to have initiated fractures in all the C module underframe bogie box locations where there were no underframe RBS fractures at location #1. The analysis also indicated RBS contact loading was unlikely to have initiated fractures at the remaining bogie box locations.

Metallurgical assessment of fractures in the welded area

2.19 An assessment of where the underframe fractures initiated and how the fractures progressed was not possible based on a visual inspection. As such a number of metallurgical assessments were undertaken to review the underframe fractures. Metallurgical reviews of the underframe RBS structure and bogie box identified evidence of fractures consistent with a mechanical fatigue failure mode. The fracture locations reviewed included fracture location #1 (underframe RBS), fracture location #2 (L bracket) and fracture location #3 (central upper bogie box sheet interface with the lower shelf) (see *Metallurgical underframe structure assessments* on page 53).

2.20 Manufacture of the Urbos 3 underframe was subject to a quality system that applied to welding fabrication. CAF's weld quality inspection requirements called for a 100 per cent visual inspection of selected bogie box welds on the first vehicle manufactured. That process required visual inspection of the L bracket construction when it was in the fully assembled state (welded into the bogie box). This meant the internal surfaces of the L bracket structure (fracture location #2) and covered sections of the central upper bogie box sheet interface with the lower shelf (fracture location #3) would not have been subject to a visual inspection. Such an inspection could have checked for any L bracket or bogie box sheet plate misalignment or weld undercutting defects that would have reduced those component's fatigue strength.

2.21 Material samples obtained from the Urbos 3 bogie box were examined to review where the fractures initiated from. The results of that review identified the fractures initiated from the; internal side of the L bracket at its welded joints, and also the covered welded joint area of the bogie box sheeting in proximity to the L bracket. The weld quality of other areas of the underframe was examined by TfNSW post incident through NDT testing. The results of those inspections identified weld quality that met TfNSW's expectations.

2.22 Based on the evidence provided, CAF's quality system did not require a full visual check of the L bracket welding construction (fracture location #2) and central upper bogie box sheet interface with the lower shelf (fracture location #3), where post incident metallurgical review identified fatigue fractures had initiated.

Procurement

Procurement standards and supply of relevant information for design

2.23 During the tendering and design review stages, TfNSW did not communicate the IWLR line track maintenance standards and actual track geometric conditions to CAF as per their request. While TfNSW provided CAF with a track design structure gauge standard and complete track geometry design drawings, the full complement of information was ultimately not sourced by CAF. The international rolling stock EN 12663 design standard applied by CAF recommended fatigue calculations be derived from multi body-simulations, previous experience, or test measurements for the operating conditions to be expected. In addition, international track maintenance standards recommended the use of actual track geometry data as an input to perform realistic simulations of vehicle and track interaction. Such information could have been sourced and used by CAF to assess the LRV design for suitability to cope with expected fatigue loading.

2.24 Testing of the Urbos 3 on the IWLR line identified expected vehicle loading (through measurement of acceleration levels) to be below that of the LRV EN 12663 design standard. However, the opportunity to validate that observation through simulation modelling with the use of actual track geometry data and track geometry maintenance standard tolerances was not undertaken. That additional work may have assisted CAF in managing the risk of underframe failure in 2013 at the design stage.

Tender assessment

2.25 CAF's tender was noted to offer an established 'World Tram' design. Up until fractures were identified in the Birmingham Fleet in late 2019, CAF had not reported experiencing that type of underframe problem in the Urbos 3 design and had a successful history of designing and building LRVs and other rolling stock for many years.

2.26 TfNSW's requirement for CAF to design and manufacture the LRVs to meet relevant international standards called for a design life of 30 years operation. CAF identified within their design hazard log the risk of underframe failure with relevant controls to manage that risk. The risk controls included a design compliant to the standards, the conduct of static weight tests, structural tests and periodic maintenance inspections being observed at defined frequencies.

2.27 TfNSW established a small team of rolling stock specialists with heavy rail design experience to oversight a review of CAF's design and FEA assessment. The review team did query CAF regarding compliance of the FEA assessment in an area of the design where there was a reserve factor of 1 (factor of 1 being compliant to the 30-year design life). CAF advised the result satisfied the EN 12663 design standard. However, the TfNSW review team did not highlight the concerns subsequently identified by TfNSW's FEA specialist post incident.

2.28 Post incident TfNSW's FEA assessment of the original design highlighted a number of areas they considered did not meet the EN 12663 design standard. Considering the post incident design review, TfNSW may have benefited from having CAF provide further justification to support those areas of their design that were close to meeting the design standard acceptance criteria.

Manufacture

2.29 In 2013, TfNSW reviewed Urbos 3 construction practices and quality control systems applied to the construction. However, that review did not assess Sydney Urbos 3 vehicles under construction and instead reviewed Urbos 3 constructed for Birmingham, United Kingdom. TfNSW missed an opportunity to carry out a sample review of how CAF applied its construction practices to the Sydney Urbos 3 LRV fleet.

Design and Acceptance testing

2.30 The EN 12663 design standard applied by CAF to the Urbos 3 specifically recognised the rolling stock class of LRV's with low floor design and limited suspension. The standard noted that fatigue loads acting on the LRV carbody structure could differ significantly from the load values provided in the standard. CAF carried out static strain gauge testing of the Urbos 3 underframe in 2012 as part of its design assessment against the design standard. CAF considered the results of those tests sufficient to support its compliance with the design standard requirements (see *Testing, commissioning and LRV acceptance* paragraphs 1.82 to 1.85 on page 40) without the need to carry out dynamic on-track strain gauge testing. While the results of the static testing demonstrated compliance with the design standard, there were no strain gauges located in close proximity of the maximum principal stress in the welded material for the vertical fatigue load case. The placement of strain gauges at that location may have assisted CAF to validate its FEA assessment of the stress magnitude and stress direction at that location (in proximity to fracture location #2 and #3). The design standard also recommended (not mandatory) verification of the design assumptions for fatigue strength by on-track tests measuring stresses.

2.31 The validation of the original Urbos 3 fatigue design through on-track dynamic stress testing did not occur on the IWLR line during the design evaluation or commission stages. That type of testing was not carried out by CAF as part of its standard commissioning process. While it was recognised that such testing was not mandatory or a preferred practice for a manufacturer, the process of dynamic strain gauge testing was a key input into the evaluation of the original and modified designs post incident.

2.32 Strain gauge testing of an LRV, at areas of predicted high stress points (hot spot areas including the maximum principal stress in the welded material), could have identified areas of the bogie central frame where fatigue loading exceeded the design standard. It was possible that additional static strain gauge testing or on-track dynamic strain gauge testing could have been undertaken to reduce the risk of underframe fatigue fractures.

Underframe and bogie configuration set-up

2.33 Urbos 3 commissioning documentation included measurement of critical carbody clearances referencing CAF's TMP standards. The measurement of those critical clearances was identified during the final vehicle assembly process. Any critical clearances measuring outside of acceptable tolerances may have been adjusted via the addition of regulating shims (metal plates). Regulation shimming could have been added to the Urbos 3 at the motor bogie drag link assembly or bogie RBS (Figure 19 on page 38). The placement of shimming in those areas had the effect of changing the RBS clearances. The maintenance of those clearances was identified by CAF as being critical to ensure RBS contact with the Urbos 3 underframe was kept to a minimum and not induce fatigue loading not accounted for in the design.

2.34 The initial Urbos 3 commissioning and acceptance certification process did not record bogie drag link shimming and bogie RBS clearance shimming. In addition, the recording of those measurements was not required as part of the ongoing CAF maintenance procedures (see *Technical maintenance plan requirements* on page 42). Recognition of the regulation shimming in the commissioning documentation may have translated into recording of that key configuration in the ongoing Urbos 3 operation and maintenance.

Track geometry standards, design and condition

2.35 Tender information provided to CAF included track design drawings that detailed several curves that did not have transition curves with cant between straight track and curved track. Post incident, CAF reported that curves, without adjoining transition curves, were not desirable as they could impact on Urbos 3 LRV loading resulting in fatigue cracking of the underframe. This was not identified by CAF in the tendering phase.

2.36 Actual track geometry data and full track maintenance standards were not provided by TfNSW to CAF during the design phase or independently sourced by CAF. That information was one of many potential information sources a LRV designer could review to assess operational forces applied to LRVs over their design life. International standards recommended vehicle design assess actual track data as a design input. Only the structural gauge outline standard was provided to CAF. That standard defined the structural envelop the LRVs were restricted to operate within. There was no record of CAF advising that the information supplied against the track standard supplied was insufficient.

2.37 Track design and maintenance standard tolerances applied to the IWLR line at the time of the Urbos 3 procurement did not appear to differ significantly to applicable international standards at that time, except for track twist limits. However, the extent of those differences was unlikely to place additional loading on the LRV beyond the EN 12663 design standard loads. That assessment was based on the premise that LRV operational loading induced from track conditions on the IWRL line, that was maintained to the different track twist limits, were measured to be below the design standard loads.

2.38 CAF's experience from their Urbos 3 February 2020 testing in Birmingham, identified that track speed limits for tight radii curves needed to be regulated to reduce the instances of RBS contact loading. CAF's recommendation in that instance was to check the posted speed limit against a Droc limit of 70 mm/s. A review of the sign posted speed limits of tight curves on the IWLR line revealed all of those curves produced Droc values below 70 mm/s, thereby satisfying the CAF observation on setting an appropriate speed limit to reduce the likelihood of RBS contact loading.

2.39 The heavy rail track geometry standard applied by Alstom (TMC 203) identified no gross non-compliances from track geometry measurement data over a two-year period prior to the incident. The data indicated there were no areas of track with twist geometry that produced any remedial work to be actioned sooner than the requirement to program the work for repair. OTSI noted the track data only identified one track twist defect in 2020 that fell under the track defect classification for remedial repair.

2.40 Track defects were noted to have reduced in 2021 from the values recorded in 2020. A review of the 2020 track defects also identified each of the defects were from a single location. The CAF ride quality testing report of July 2014 and on-track dynamic testing report of April 2022 to May 2022 did not identify the need to consider changes in speed arising from the track geometry condition experienced.

2.41 The investigation did identify some evidence suggesting LRV track curve design transitions on other sections of the IWLR line exceeded the TfNSW acceptable passenger Droc safety limit of 37 mm/s. It was noted that threshold could impact passenger safety increasing the likelihood of passenger falls within the LRV at those locations. However, OTSI noted the Urbos 3 commissioning testing of 2014 identified the LRVs satisfied the CAF *Ride Comfort and Safety Against Derailment* standard as per international standard and code.[87]

[87] CAF ride quality testing report (*Ride Comfort and Safety Against Derailment)* referenced EN 12299 Railway Applications – Ride comfort for passengers – Measurement and evaluation. April 2009 and UIC CODE 518 Testing and approval of railway vehicles.

Urbos 3 technical maintenance plan instructions

RBS clearance management

2.42 CAF's technical maintenance plan (TMP) instructions detailed certain requirements for checking C module RBS clearances and maintaining bogie drag link regulation shimming. The application of those requirements would have reduced the potential for RBS clearances to become out of tolerance and reduce the likelihood of RBS contact loading.

2.43 Checking of the RBS clearances was required when an RBS needed to be changed due to wear and when a bogie had been reassembled. There was no requirement in the related bogie change procedure for RBS clearances to be checked and recorded. Conversely CAF required each LRV unit to have RBS clearances measured and recorded during their factory testing certification prior to delivery. The procedure relating to checking RBS clearances remained unchanged while CAF Australia (December 2013-June 2015) and Alstom (July 2015 to October 2021) maintained the LRVs up to the incident.

2.44 Maintenance records provided by Alstom identified there was only two bogie RBS changed out in the Sydney Urbos 3 fleet since they commenced operation in 2014. The frequency of checking RBS clearances due to the change out rate requirement would have been minimal based on the actual RBS changeout frequency. Checking of RBS clearances was also required when a bogie was reassembled. Application of the bogie reassembly procedure, required in the first instance, for the bogie to be removed from the LRV. However, there was no reference within the bogie reassembly procedure of the need to place the bogie back under the LRV to complete a check of the RBS clearances. As such the checking of RBS clearances on a bogie reassembly did not occur on completion of that maintenance task. The absence of carrying out a check of RBS clearances on reassembly of a bogie was not identified by TfNSW, ALTRAC, Transdev or Alstom prior to the incident. In addition, the requirement to check RBS clearances without the bogie being placed under the LRV was not addressed in the Sydney Urbos 3 bogie reassembly procedure by CAF prior to the incident.

2.45 The critical tolerance to minimise the likelihood of RBS contact was identified by CAF within the TMP as 14 mm. As per the TMP a bogie RBS (4 per bogie) could be shimmed by up to 5 mm to meet the minimum clearance. That shimming may have occurred at either the initial time of delivery (2013), or when an RBS was changed out. If that shimming was not removed and/or RBS clearances checked when a bogie was interchanged under another C module, the resulting RBS clearance could have recommenced at 9 mm. That scenario was possible considering the post incident RBS clearances measured on the Sydney Urbos 3 fleet identified 6 instances of RBS clearances below 10 mm. In addition, there were 34 RBS clearances below 14 mm (37 per cent out of tolerance) where those clearances could have been affected by other combinations of inappropriate RBS shimming.

2.46 The RBS clearance could have also been adjusted through the addition or removal of drag link regulation shims. The addition or removal of a regulation shim could have occurred during the interchanging of a motor bogie between LRV C modules. While the maintenance procedure covering that process required drag link shimming to be respected, there was no documented registration of that shimming configuration to assist in managing the process.

2.47 It was not apparent to TfNSW, ALTRAC, Transdev or Alstom for the need to carry out checking of RBS clearances during the maintenance activity of a bogie being interchanged with another bogie. That activity being when it was most likely RBS clearances could become out of tolerance. In addition, the CAF TMP did not account for a bogie being interchanged as a standard practice. It was likely TfNSW, ALTRAC, Transdev and Alstom were not mindful of the CAF restriction on interchanging bogies as:

- The ability to interchange a bogie between rolling stock of the same class was a standard heavy rail practice at the time of the Urbos 3 procurement. If there were special procedural requirements to permit the interchangeability of bogies, those requirements would have expected to be documented in a related procedure. The TfNSW Urbos 3 supply contract stipulated for the ability to interchange bogies between LRVs, with that option being originally identified by CAF. Following the procurement stage, no communication between TfNSW and CAF could be found which detailed CAF's conditions or warnings on not providing for a bogie to be interchanged as a standard practice in the TMP. CAF's single TMP condition of ensuring that bogie drag link shimming was to remain the same was not understood by TfNSW, ALTRAC, Transdev or Alstom to mean that the same bogie must remain configured to its existing C module unit.
- The related TMP procedure was titled 'motor bogie – change' with an inference in the title that suggested a motor bogie was changed through application of the procedure.
- There was no documented process to check the RBS clearances during the bogie change maintenance procedure.
- There was no requirement within the TMP to record the RBS clearances at any stage during the other maintenance activities.

2.48 In February 2020, CAF established the critical nature of Urbos 3 RBS clearance management through their testing of reduced RBS clearances on the Birmingham network. During that testing CAF established a correlation between a reduction of RBS clearances and increased bogie to underframe RBS contact frequency and force. That correlation occurred when LRVs traversed straight track to tight curves with no transition curves and the track speed was not set within specified limits.

2.49 In August 2020, CAF Australia introduced an additional TMP procedure to record RBS clearances and drag link regulation shimming into its maintenance of the Urbos 3 fleet operating on the Canberra light rail line. That procedure required the RBS clearances to be measured when a bogie was reinstalled under the carbody and required the recording of drag link regulation shimming arrangements pre and post bogie change. A similar documented procedure was not communicated to TfNSW nor introduced into the Sydney Urbos 3 TMP at that time. Changes to the TMP could have been made by TfNSW on recommendation from CAF to account for the configuration issues identified, thereby reducing the risk of bogie RBS contact with the underframe. As there was no requirement to record RBS clearance measurements within the TMP the investigation could not confirm or discount if the RBS clearances were within tolerance since Urbos 3 operations commenced in 2014.

Underframe fracture inspection requirements

2.50 CAF's TMP covering the underframe inspection for fractures could have been improved to guide a maintainer in the identification of RBS fractures. CAF's TMP did not include a reference figure detailing the various structural components that required inspection and relied on descriptions of structural components to provide a focus on the areas to inspect. In addition, the general arrangement drawings applied terms to identify structural components of the Urbos 3 underframe that were not duplicated in the TMP descriptions. As such the general arrangement drawings did not provide a clear supporting reference to identify the location of components described in the TMP. The TMP also contained some English terms and phrases that required interpretation by Alstom considering the TMP's initial translation from Spanish to English. Certain maintenance practices were followed, based on Alstom's interpretation of the TMP and general assembly drawings, that were likely to limit the opportunity of fractures being detected in the underframe RBS, for instance:

a. The TMP instruction CAJ-00-003 'Underframe – Inspect Visually' required inspection for fractures of 'longitudinal', 'cross members' and 'carbody brackets' during an 'IS' inspection every 15 days. The inspection process was to be carried out with an LRV in the 'moat' with Alstom interpreting that inspection for fractures to focus on the central frame area only (green area shaded in Figure 21 on page 46). As a consequence, that inspection did not focus on the underframe RBS structure (considered to be a carbody bracket) or review for fractures around the pneumatic sanding equipment carbody bracket (Figure 6 and Figure 7 on page 16). Those items being external to the central frame and also in proximity of where the RBS fractures were detected. Detection of the RBS fractures did not occur until a maintenance technician from a different depot identified the fractures from outside of the 'moat' as part of an 'IS' inspection where an inspection of the underframe for any loose cables, pipes and supports was also required.

b. The general arrangement drawings identified a number of relevant structural components as 'side cross-beams', 'cross-beams', and 'reinforcements' (Figure 21 on page 46). Alstom recognised the TMP descriptions of 'longitudinal' as side cross-beams and 'cross members' as cross-beams when applying the TMP. Those components required inspection as per the TMP instruction CAJ-00-003 'Underframe – Inspect Visually' (see page 45). Reinforcements were not recognised by Alstom as either a longitudinal or cross member in the context of the TMP. As such reinforcements were not considered to require inspection for fractures as they were external to the central frame and not a structural component considered by Alstom as being noted for inspection. Fractures were identified post incident in the reinforcement members as depicted in Figure 6 on page 16.

2.51 There was also a section of the TMP where further guidance could have been provided to direct maintenance technicians in checking of underframe RBS condition, in the same way guidance was provided to inspect the underframe LBS condition during a bogie inspection (see *Technical maintenance plan requirements* on page 42). A duplicated underframe RBS inspection requirement would have provided a greater focus on that structure for the potential detection of fractures. Such guidance may have assisted in targeting those areas of the underframe that were difficult to inspect considering the extent of thick underframe underbody paint and noise abatement material that may have concealed the detection of fractures.

Training of technical maintenance staff

2.52 In September 2021 fractures were identified by a maintenance technician in an underframe RBS gusset during a 30 day 'IS' inspection.[88] The maintenance inspection regime was ultimately successful in the detecting the presence of those fractures prior to any potential incident taking place, such as an underframe failure resulting in a derailment. However, the training and competency assessment system of both CAF Australia and Alstom was not documented to cover a maintenance technician's visual inspection of the Urbos 3 underframe for fractures.

2.53 CAF Australia did not carry out formalised training and competency assessment of maintenance technicians covering inspection of the underframe for fractures while it was the Sydney Urbos 3 maintainer between December 2013 to June 2015.

2.54 As at the time of the incident, Alstom applied a process to train and competency assess its maintenance technicians in inspecting Urbos 3 LRVs as per the TMP requirements. That process was advised to cover a maintenance technician's inspection of the Urbos 3 underframe for fractures. However, the process did not have in place documented training or competency assessment records to verify when and how it was conducted.

2.55 Transdev's SMS detailed that rail safety workers had comprehensive records of individual competence and training captured. The records of Alstom were not found to be comprehensive to support that requirement.

Urbos 3 maintenance and underframe fracture detection

2.56 Operation of the Urbos 3 LRVs was suspended in late October 2021 after the LRVs had been in-service for approximately 7 years. Eleven (11) of the Urbos 3 LRV fleet had travelled approximately 533,000 kms at the time of their suspension. The remaining one (1) LRV (U2123) had travelled 386,000 kms. The reduced number of kilometres travelled by U2123 was due to the vehicle being removed from service at various times for unscheduled work not related to the incident.

2.57 The extent of underframe fractures on U2123 was similar or worse compared with other LRV units such as U2112, U2115, U2120 and U2121. Considering the distance travelled of U2123 and the other LRV units, there was potential that fractures in the RBS had become visible in the fleet after approximately 5 years of operation (being two years prior to their initial discovery in September 2021). That assessment assumed that all LRV units experienced similar passenger loading, track conditions and were driven at similar speeds during their operation.

2.58 The Urbos 3 TMP required an inspection of the bogie RBS at an 'IS' inspection (every 15 days) and 'P1' inspection (after 70,000 kms), being in the vicinity of the underframe RBS fracture location #1. While an 'IS' inspection detected the first underframe fractures, there was potential for a similar inspection to have detected those fractures in the underframe RBS prior to September 2021. However, the detection of fractures in the underframe at locations #2, #3, #4 and #5 would have been unlikely without any specific TMP direction to focus on those areas. OTSI estimates there were approximately 600 LRV unit inspections that had occurred

[88] The inspection frequency for 'IS' inspections was extended to 30 days in June 2021 during the COVID pandemic as a result of a COVID outbreak at the depot that impacted on staffing levels. The change in inspection frequency was supported via a risk assessment.

on the LRV fleet since September 2019, where those inspections had the potential to detect fractures in the underframe RBS structure in the same way it was detected in September 2021.[89] It was possible the likelihood of detecting fractures in the vicinity of the RBS underframe was reduced due to:

- Maintenance technicians becoming desensitized from identifying potential fractures considering the extent of underbody sealant shrinkage lines that appeared along welded joints and component transition lines (Figure 7 on page 17).
- A general expectation that fractures of the type identified in the RBS structure would not occur in a fleet of 7 years old. CAF's targeted inspection for potential fractures in the underframe pivot beam assembly (Figure 19 on page 38) was due to occur after approximately 15 years of operation.
- The 'IS' TMP instruction covering a **bogie inspection** did not specifically require a check of the underframe RBS condition in the same way it required a check of the LBS underframe condition. No fractures were identified in the LBS underframe area (Figure 20 on page 44).
- The 'IS' TMP instruction covering the **underframe inspection** for fractures did not specifically require a check of the underframe RBS condition. Alstom interpreted that inspection of the underframe RBS structure was outside the fracture inspection area. Alstom interpreted the TMP to require inspection for underframe fractures in the central frame area only (green area shaded in Figure 21 on page 46).
- The Urbos 3 training and competency assessment system of Alstom was not documented. Documentation of the system may have assisted in reliably reinforcing all relevant CAF TMP instructions.

Monitoring of Urbos 3 speed on the IWLR line

2.59 There was no historic automated reports available that assessed LRV operation with the posted speed limits. As such there was no reliable means to assess if the LRVs were exceeding the posted speed limit on tight curves where CAF had concerns of RBS contact loading causing underframe fractures.

2.60 A TfNSW loading simulation was carried out to assess the impact of a 10 per cent increase in speed on RBS contact. The loading simulation concluded that a 10 per cent speed increase was unlikely to have an impact on fatigue loading of the LRVs. Based on the available Urbos 3 speed monitoring and assessment information, OTSI's investigation could not identify LRV overspeed as contributory to the initiation of underframe fractures.

Organisational response to identification of Urbos 3 underframe fractures

2.61 Underframe fractures were identified in the Birmingham, United Kingdom Urbos 3 fleet in late 2019. In February 2020 CAF determined the root cause of underframe fractures in the Birmingham fleet being due to bogie RBS contact loading with the underframe RBS. Certain

[89] The 600 inspections being based on; 24 x IS inspections per year per LRV unit and 1 x PI inspection per year per unit, over 2 years on a fleet of 12 LRV Units.

operational conditions were also identified to increase the likelihood of RBS contact loading with these being:

- RBS clearances not meeting the TMP tolerances
- Excess LRV speed into and out of tight curves without adjoining transition curves and suitable track cant in those curves.

2.62 On 11 June 2021 operation of the Birmingham Urbos 3 fleet was suspended due to additional fractures detected in the bogie box area. CAF advised TfNSW of the fractures in the Birmingham fleet 3 days (14 June 2021) after the services there were suspended.

2.63 CAF's statement to its customers on 14 June 2021 (Urbos 3 owners including TfNSW) informed them of the general area ('steel over the bogie') where the fractures had been found. However, they did not the detail the specific underframe fracture locations, how they considered the fractures had occurred and the operational conditions to be checked to confirm if those conditions were present in their customer's operations. It was not until 15 September 2021 that CAF provided TfNSW with details as to how they considered the fractures had occurred. CAF provided the same advice to ALTRAC and Transdev a few days later (21 September 2021).

2.64 No proactive inspections of the Sydney Urbos 3 LRVs for underframe fractures or the conditions under which they were considered to have occurred were carried out by any organisation. TfNSW, ALTRAC, Transdev and Alstom's prior experience with CAF followed that any checking of LRVs for concerns raised from overseas operations occurred because of a CAF direction. Regardless of that prior experience, an opportunity existed for TfNSW (from 15 September 2021), ALTRAC, Transdev or Alstom (from 21 September 2021) to direct for proactive inspections to take place to check for either:

- the presence of RBS underframe fractures, or
- the conditions under which CAF considered they had occurred.

2.65 CAF had not advised TfNSW of earlier Birmingham Urbos 3 underframe fractures in February 2020, as they considered the fracture cause was due to operational conditions and not due to potential underframe design problems.

2.66 CAF's SMS contained provisions for identification of potential hazards in their designs and provided scope for taking necessary action in response to those hazards. CAF's proactive inspections of potential door portal fractures in the Sydney Urbos 3 fleet in May 2021 followed identification of similar fractures in the Birmingham fleet. Those proactive inspections were consistent with the CAF SMS. No specific recommendation was made by CAF to inspect the Sydney Urbos 3 fleet for fractures in the underframe RBS or bogie box area.

2.67 ALTRAC's SMS contained provisions to assess safety risks arising from incidents and investigations. ALTRAC's SMS provided for LRV risks to be captured by Transdev within it's corporate risk register. A risk register entry was made by Transdev in October 2021 to include the identification of risk arising from the RBS fractures detected in the Sydney Urbos fleet on 27 September 2021. Actions of investigation were entered against that risk register entry. A similar risk was not added to the register in June 2021 or September 2021 when CAF communicated the risk to ALTRAC via TfNSW. Transdev advised that proactive inspections were not considered necessary in June 2021 due CAF's express advice that no such inspections were required, and their prior experience with CAF typically directing for proactive inspections to take place when necessary.

2.68 TfNSW's SMS dealing with risk management applicable to light rail operations prescribed requirements for dealing with assessing configuration change management risks. The TfNSW SMS also identified a requirement for TfNSW to manage risks associated with the ongoing operation of its assets being maintained on its behalf. However, the details of the TfNSW SMS did not cover specific guidance on the expectations of how TfNSW should assess safety incident information relating to its LRV assets.

Safety actions taken in response to the LRV underframe fractures

2.69 A significant number of post incident safety actions were undertaken and coordinated by TfNSW, CAF, ALTRAC, Transdev and Alstom in order to address the potential risks identified as a consequence of the Urbos 3 underframe fractures. A number of the safety actions that relate to OTSI's investigation findings are detailed below.

Communication of any further Urbos 3 safety issues to TfNSW

2.70 TfNSW made an amendment within their supply contract with CAF for the 4 new Urbos LRVs being procured to expand the Urbos 3 fleet operating on the IWLR line. The amendment included an obligation relating to 'Notifiable Faults'. This obligation required CAF to provide notice within 20 business days of any defects (including design fault) or a material operational issue which occurred in any vehicle in the newly designed Urbos fleet anywhere in the world, and which may impact safety and reliability of any LRV. This included the original 12 IWLR LRVs, the additional LRVs procured for Newcastle and the additional 4 ordered for the IWLR line. That requirement was for the design life of the LRVs. The notice period for safety issues was as soon as practicable.

Original Urbos 3 design re-evaluation

2.71 Extensive dynamic on-track testing was carried out by TfNSW and CAF to inform themselves of how the Urbos 3 original design performed on the IWLR line in compliance with the LRV EN 12663 design standard requirements (see *On-track dynamic vehicle testing* on page 58).

2.72 CAF and TfNSW carried out their respective technical investigations into the underframe fractures and provided the results of their investigations to OTSI (see *Urbos 3 Underframe failure assessments* on page 66).

Modified Urbos 3 design evaluation, repair program and return to service

2.73 CAF prepared a modified bogie box design and repair procedure with that work being accepted by TfNSW as part of the Urbos 3 return to service program (see *Modified Urbos 3 design* on page 70).

2.74 CAF, TfNSW, ALTRAC, Transdev and Alstom implemented the Urbos 3 repair program which included refabrication of the bogie box as per the modified design.

2.75 CAF and TfNSW carried out another extensive dynamic on-track testing program to inform themselves of how the Urbos 3 modified design performed on the IWLR line in compliance with the LRV EN 12663 design standard requirements (see *Urbos 3 modified design - CAF dynamic* *testing results – April and May 2022* on page 61 and *Urbos 3 modified design - TfNSW dynamic testing results – May 2022* on page 62).

2.76 CAF developed an underframe fracture inspection report that recommended an initial program of underframe inspection in discrete areas to check for any fractures in the modified design. TfNSW and Alstom carried out those inspections as per the CAF recommendation with no fractures being identified.

2.77 TfNSW permitted the return to service of the Urbos 3 repaired vehicles following approval from a configuration control board, with that approval being subject to passing an independent assurance report. Urbos 3 LRV units started to return to service from 1 August 2022 after each unit had progressed through the repair and modification program.

2.78 Alstom carried out a fracture inspection program as per CAF's recommendation to review the modified bogie box 6 months after the fleet returned to service. The results of that review did not identify any fractures within the C module modified bogie box and RBS underframe structure.

Part 3 — Findings

From the evidence available, the following findings are made with respect to the removal from service of the Sydney Urbos 3 fleet in October 2021, following detection of underframe fractures.

Contributory factors

3.1 The 2013 Sydney Urbos 3 underframe bogie box design was not sufficient to last the required 30-year operation considering cyclic loading at key structural locations. Those design deficiencies were not identified in the designer's finite element analysis that was reviewed and accepted by the asset owner.

3.2 The maintenance regime was not sufficient to detect the presence of fractures in the underframe rotation bump stop (RBS) and L bracket locations that were likely to be in place for months prior to the vehicles being withdrawn from service.

3.3 The maintenance regime did not take timely action to initiate proactive inspections of the underframe bogie box locations despite their being knowledge of similar factures identified in overseas Urbos 3 vehicles, and considering the risk of Light Rail Vehicle (LRV) derailment due to a fractured underframe.

Other safety factors

3.4 The 2013 Sydney Urbos 3 manufacturing quality system did not require a full visual inspection of the quality of L bracket welds and some other bogie box sheet welds where fractures were identified to have initiated.

3.5 Rotation bump stop (RBS) clearances on a number of C modules were identified to be out of tolerance whereby contact between the bogie RBS and underframe could result. The operation of Urbos 3 LRV's with RBS clearances below the technical maintenance plan tolerance, increased the risk of RBS contact forces not considered in their 30-year design.

3.6 The opportunity existed to carry out additional strain gauge testing of the 2013 Urbos 3 underframe bogie box design to validate it against the EN 12663 design standard. That additional testing could have focused on the major principal stresses in the welded material to verify the stress level and direction was consistent with bogie box design assumptions. Such testing may have occurred at either the 2012 static strain gauge testing or through on-track strain gauge testing during the LRV commissioning stage. The conduct of that additional testing would have been consistent with the LRV design standard in place at the time of the Urbos 3 procurement in support of managing the risk of underframe failure.

3.7 The opportunity existed for actual track geometry data and track maintenance standards intervention limits to be used for assessment as part of the Urbos 3 design phase. The use of that information would have been consistent with the LRV EN 12663 design standard in place at the time of the Urbos 3 procurement in support of managing the risk of underframe failure.

3.8 The option to interchange C module bogies between Urbos 3 units was specified at procurement. However, the conditions by which a bogie could be interchanged was not clearly communicated within the TMP, identified at the time of Urbos 3 acceptance in 2014 and understood during their operation until the incident. As such, the risks arising from incorrect RBS clearances on interchanging bogies between C modules were not considered.

3.9 The Urbos 3 technical maintenance plan instructions did not provide clear guidance covering inspection of the underframe RBS for fractures and ensuring the required RBS clearances were maintained during bogie changes. This increased the likelihood of vehicles operating with undetected underframe fractures and reduced RBS clearance causing more frequent RBS contact with the underframe.

3.10 The training and competency assessment of Urbos 3 maintenance staff in the conduct of underframe and bogie inspections was not supported by a documented process to provide consistent verification the staff were competent to carry out those inspections. While the maintainer could show the competency status of its maintenance staff at any point in time, their training and competency assessment process was not supported by records to validate the training and assessments carried out.

3.11 A number of IWLR track geometry design locations exceeded the track owner's passenger safety standard of superelevation deficiency (Droc value) at 37 mm/s. However, the Urbos 3 LRV vehicles were noted to have passed the commissioning test of Ride Comfort and Safety Against Derailment standard that referenced the EN 12299 Railway Applications – Ride comfort for passengers – Measurement and evaluation standard.

Part 4 — Recommendations

Noting that some remedial safety action has already been implemented, it is recommended that the following additional safety actions be undertaken by the specified responsible entity.

Alstom

4.1 Continue to progress and finalise improvements in the Urbos 3 training and competency assessment system in the conduct of underframe and bogie inspections.

4.2 Consider a program to rotate technical staff across vehicles to provide an opportunity for staff to work on different vehicle types.

ALTRAC

4.3 Undertake audit activities to provide assurance that the Urbos 3 training and competency assessment system is in accordance with the ALTRAC Safety Management System.

4.4 Review the ALTRAC Safety Management System to determine if further guidance is required to cover when proactive investigations of original equipment manufacturer reported light rail vehicle (LRV) component failures are undertaken. The decision to undertake proactive investigations should consider if it would be reasonable to expect similar LRV failures could be possible.

Construcciones y Auxiliar de Ferrocarriles (CAF)

4.5 Review its light rail vehicle (LRV) structural design processes to consider improving validation practices in the areas of:

a. Selection of appropriate weld categories to apply against welds identified in the finite element analysis to be on the boundary of compliance with the fatigue load design standard. The selection practice should consider the sensitivity of the weld assessment category chosen (in terms of stress direction) to meet the required design life.

b. A focus on validating those areas of major principal stresses in the weld material, derived from fatigue load cases, in terms of both stress magnitude and direction. The validation of those principal stresses may consider assessment through either static or on-track strain gauge testing using a risk-based approach.

c. Sourcing its customers relevant track maintenance defect limit standards and measured track geometry data to verify LRV designs can cope with those variables over their required design life.

4.6 Review the CAF welding quality assurance process covering the selection of welds to consider including critical structural welds that would not be possible to review once assembly of the fabricated structure is complete.

4.7 Review the CAF commissioning and acceptance certification process for LRVs of a similar bogie configuration to the Urbos 3 to consider recording of bogie drag link shimming and bogie rotation bump stop clearance shimming configurations.

4.8 Review and update the generic Urbos 3 technical maintenance plan (TMP) procedures to provide further guidance on:

a. When the measurement of rotation bump stop (RBS) clearances are to be carried out to provide confidence the RBS clearances are maintained within the TMP tolerances. The review should also consider the benefits of recording the RBS clearance measurements, RBS shimming configuration and drag link configuration as a means to ensure reliability of achieving RBS clearances when bogies are interchanged.

b. Any areas of the Urbos 3 underframe that require a periodic inspection to check for the presence of fractures, where the location of those areas have been identified through its finite element analysis (FEA) of the Urbos 3 design.

c. Any areas of the Urbos 3 underframe that require a periodic inspection to check for the presence of fractures considering the structural component terms within the CAF assembly drawings and any different terms used within the TMP.

4.9 Provide additional guidance within the CAF Safety Management System covering the need to advise its light rail vehicle (LRV) clients of potential LRV component failures that have been discovered in similar CAF manufactured vehicles. Such guidance is recommended to include information of the associated safety risk, method of how the component is to be inspected and any necessary maintenance actions.

Transport for NSW (TfNSW)

4.10 Review the TfNSW procurement process to consider any additional designer reporting requirements identified by the TfNSW finite element analysis (FEA) design review of CAF's Urbos 3. Consideration should be given to expanding the structural analysis reporting requirements to identify and provide relevant justification of those areas which are on the boundary of meeting the 30-year design life standard.

4.11 Review the TfNSW procurement process applicable to acquisition of LRVs to consider supply of its light rail track maintenance standards and actual measured track geometry data to assist designers to verifying their designs are sufficient to meet the required design life.

4.12 Review the TfNSW procurement process and standards applicable to commissioning of LRVs on the TfNSW network to consider:

a. Inclusion of on-track dynamic strain gauge testing for the purpose of validating suitability of LRVs to meet their specified design life using a risk based approach.

b. TfNSW's requirements traceability processes check LRV design requirements (such as the interchanging of bogies) to ensure those requirements are assessed and validated prior to LRV acceptance.

4.13 Review and approve light rail vehicle bogie maintenance and underframe inspection updates to the Sydney Inner West Light Rail Urbos 3 Technical Maintenance Plan (TMP) procedures. The review and approval should be supported by advice from a technically competent organisation with changes made to improve further guidance on:

a. When the measurement of rotation bump stop (RBS) clearances is to be carried out to provide confidence the RBS clearances are maintained within the CAF TMP tolerances. The review should also consider the benefits of recording the RBS clearance measurements, RBS shimming configuration and drag link configuration as a means to ensure reliability of achieving RBS clearances when bogies are interchanged.

b. Any areas of the Urbos 3 underframe that require a periodic inspection to check for the presence of fractures, where the location of those areas have been identified through TfNSW's Urbos 3 design reviews.

c. Any areas of the Urbos 3 underframe that require a periodic inspection to check for the presence of fractures considering the structural component terms within the CAF assembly drawings and terms used within the TMP.

4.14 Review the TfNSW Safety Management System (SMS) to determine if further guidance is required to direct its maintenance provider to proactively investigate reported original equipment manufactured light rail vehicle (LRV) component failures. The decision to undertake proactive investigations should consider if it would be reasonable to expect similar LRV failures could be possible.

4.15 Review the light rail track geometry standard to ensure it is fit for purpose to manage passenger safety requirements consistent with the relevant light rail vehicle ride comfort for passengers measurement and evaluation standard.

Part 5 — Glossary

Alignment	Alignment of track may be referred to as horizontal or vertical alignment. Horizontal alignment is the design horizontal alignment of track (i.e. straights, curves, etc.), vertical alignment is the design vertical alignment of track (gradients and vertical curves).
Alstom	Alstom Transport Australia Pty Ltd (Alstom) was the Urbos 3 maintainer subcontracted by Transdev and was responsible for the maintenance of all IWLR infrastructure assets in accordance with the TMPs from July 2015. The infrastructure included the Urbos 3 LRVs, track, signalling and train control assets.
ALTRAC	The accredited light rail operator from August 2018. ALTRAC was contracted by TfNSW to operator and maintain the Urbos 3 on the IWLR line. ALTRAC had in place a subcontract arrangement with Transdev to perform that role. Transdev had a subcontract arrangement with Alstom to maintain the LRVs on Transdev's behalf.
AW0 to AW5 LRV mass	Dynamic testing of Urbos 3 on the IWLR line was carried out using various passenger loading. The TfNSW (AW#) and CAF (EL #) LRV loading values applied included: - AW0 (EL E) LRV mass without passengers (tare) - AW1 LRV mass with all seats occupied, without standing passengers - AW2 (EL 4) LRV mass at normal capacity with all seats occupied, 4 passenger/m^2 standing - AW3 LRV mass with all seats occupied, 5 passenger/m^2 standing - AW4 (EL 6) LRV mass with all seats occupied, 6 passenger/m^2 standing - AW5 LRV mass at "exceptional" capacity with all seats occupied, 8 passenger/m^2 standing.
Bogie	A structure incorporating suspension elements and typically fitted with wheels and axles, used to support rail vehicles at or near the ends and capable of rotation in the horizontal plane. LRV bogies had axle bridge assemblies to support the 4 wheels of a bogie.
Bogie box	The bogie box area of an Urbos 3 LRV was a section of the underframe where the LRV bogie was connected to the LRV carbody and where the weight of the carbody acted on the bogie.
CAF Australia	CAF Rail Australia Pty Ltd was the maintainer of the Variotrams, Urbos 2 and then Urbos 3 LRV fleet from November 2012 until June 2015.
CAF	Construcciones y Auxiliar de Ferrocarriles was the designer and manufacturer of the Sydney Urbos 3 fleet.

Cant	Also referred to as Superelevation, is used for intended height difference in the rails (i.e. where the track is inclined in a curve), and the term 'cross-level' is used for the unintended height difference (i.e. due to track irregularity). The term used to denote the raising of the outer rail on curved track to allow higher speeds than if the two rails were level. Cant compensates for the centrifugal force arising from a train traversing a curve.
Cant Deficiency	Track cant deficiency is the amount by which the applied track cant would have to be increased to equal the equilibrium cant. Equilibrium cant is the theoretical cant at when the resultant of the train's centrifugal force and the train's perpendicular vertical force taken across the tops of rails occurs is balanced at a given speed. In this situation there is no net lateral force on the train.
Cant Ramp	A transition in applied cant to the track, usually at the entry or exit to a curve, which by design varies from a maximum value to zero, or vice versa, over a prescribed length of track.
Cumulative fatigue	Cumulative fatigue is the sum of a measured fatigue level estimated for a 30-year design life. Cumulative fatigue damage results denote the ratio of calculated cumulative fatigue at a strain gauge location over the applicable weld detail category fatigue limit (Figure 15 on page 30 for the relevant fatigue limits).
Derailment	An incident in which one or more wheelsets run off the track.
Drag link	A longitudinal connecting rod between the bogie and carbody underframe (Figure 19 on page 38).
Droc	The rate of change in track cant deficiency expressed as mm/s being calculated over a section of curved track.
Fatigue	The weakening and failure of material subjected to stress. A fatigue mode fracture in metal occurs as a result of cyclic loading with the loading lower than that necessary to cause fracture in a single loading application.
FEA	Finite element analysis. A computerised numerical analysis technique used for solving differential equations to primarily solve mechanical engineering problems relating to material stress analysis.
Gradient	A measure of the rate at which track is inclined (rising or falling).
IWLR	Inner West Light Rail
IS	Refers to a category of maintenance inspections carried out on the Urbos 3 every 15 calendar days. The inspection frequency was extended to 30 days during a COVID outbreak at the Transdev Lilyfield depot in September 2021.
kN	Kilonewton. A single Newton is a derived unit expressed in terms of the base units kilogram (kg), metre (m), and second (s), and can be written as $kg \cdot m/s^2$.

Kt	A stress concentration factor. Kt is a dimensionless factor used to quantify how concentrated the stress is in a mechanical part.
L bracket	An L shaped fabricated channel section welded into the bogie box structure. Details of the L bracket are depicted in Figure 14 on page 29.
LBS	Lateral bump stop, being a metal structure welded to the LRV underframe that consisted of a vertical contact pad. An LBS would limit the horizontal movement of an LRV C module bogie operating through curved track.
LRV	Light rail vehicle
Misalignment	A substantial displacement of track from its original design alignment caused by longitudinal thermal stresses overcoming the lateral resistance of the track.
Module	Refers to a number of light rail vehicle types, when connected make up a complete unit. Urbos 3 light rail vehicle modules can be either a C1, S1, R, S2 or C2 type.
MPa	A megapascal (MPa) is a unit of material stress or pressure. One megapascal is equal to one million pascals, which is the single unit of stress or pressure. One Megapascal (MPa) is equivalent to one N/mm^2.
NDT	Non-destructive testing applied on the LRV underframe that included dye penetrant testing (DPT) where surface-breaking defects were identified using a pink liquid dye.
N/mm^2	The unit N/mm^2 stands for Newton per square millimetre and is a unit of pressure representing force per unit area. One N/mm^2 is equivalent to one Megapascal (MPa).
ONRSR	Office of the National Rail Safety Regulator which accredited the light rail operator under the Rail Safety National Law NSW 2012.
RBS	Rotation bump stop, being a metal structure welded to the underframe that consisted of a vertical contact pad. An RBS would limit the turning rotation of an LRV bogie operating through curved track.
SAR	Safety Assurance Report
SFAIRP	So far as is reasonably practicable
SMS	Safety Management System
Strain	The amount of elongation or compression that occurs in a metal at a given stress or load.
Strain gauge	A strain gauge is a device used to measure the strain (deformation) of an object when a force is applied. The gauge detects changes in electrical resistance as the object deforms. Strain gauges work by relating the change in resistance of the gauge to the strain in an object.
Rosette strain gauge	An arrangement of multiple strain gauges positioned closely together to measure strain in different directions on a component. The rosette setup is often used as a single strain gauge can only measure strain in one

	direction, which can be insufficient for the assessment of complex structures and loads.
Stress	Force per unit area, often thought of as force acting through a small area within a plane. Unit of measurement N/mm^2 or MPa.
Superelevation	Also referred to as track cant, is used for intended height difference in the rails (i.e. where the track is inclined in a curve), and the term 'cross-level' is used for unintended height difference (i.e. due to track irregularity). The term used to denote the raising of the outer rail on curved track to allow higher speeds than if the two rails were level. Cant compensates for the centrifugal force arising from a train traversing a curve.
TfNSW	Transport for NSW was the IWLR rolling stock and infrastructure asset owner who accepted the Urbos 3 LRVs for operation following their commissioning from July 2014. TfNSW also managed the review and approval of the TMP maintenance standards and had in place a contract with ALTRAC since December 2014 to operate and maintain the Urbos 3 LRVs.
TMP	Technical Maintenance Plan that contained LRV maintenance procedures and instructions.
Track gauge	The distance between the inside running (or gauge) faces of the two rails making up track, measured between points 16 mm below the top of the rail heads.
Transdev	Transdev Sydney Pty Ltd (Transdev) was the Urbos 3 operator that employed all LRV operational staff which included drivers and light rail control staff. Transdev held accreditation for the Urbos 3 operation from July 2014 until August 2018. Transdev was contracted by ALTRAC for the operation and maintenance of the Urbos 3 on the IWLR line. Transdev subcontracted the Urbos 3 maintenance to Alstom.
Transition curve	A curve of uniformly varying radii used to connect straight and curved tracks or curves of different radii.
Underframe	Railway vehicle base which forms the support for the body structure or is an integral part of a body shell.

Part 6 — Appendices

Appendix 1: Sources, submissions and acknowledgements

Sources of information

- Alstom
- ALTRAC
- Construcciones y Auxiliar de Ferrocarriles (CAF)
- Transdev
- Transport for NSW

References

CAF underframe assembly drawings.

CAF maintenance procedures and instructions

CAF Structural Calculation Report

CAF Structural Specification Report

CAF Static Strain Gauge Report

CAF and TfNSW Dynamic Testing Reports

Canberra Light Rail freedom of information documents

EN 12663-1 Structural requirements of railway vehicle bodies Part 1

IEC-61133 - Railway applications - Rolling stock standard on completion of construction and before entry into service.

EN 12663 Structural requirements of railway vehicle bodies (the LRV design standard)

EN 15227 Crashworthiness requirements for railways vehicle bodies

EN 12299:2009 Railway applications - Ride comfort for passengers - Measurement and evaluation

UNE-EN 50215:2001 Railway applications - Testing of rolling stock after completion of construction and before entry into service.

TfNSW IWLR line track geometry drawings

TfNSW light rail standards

TfNSW Urbos 3 procurement contract and technical specification

RailCorp track design and maintenance standards

Submissions

The Chief Investigator forwarded a copy of the Draft Report to the Directly Involved Parties (DIPs) to provide them with the opportunity to contribute to the compilation of the Final Report by verifying the factual information, scrutinising the analysis, findings and recommendations, and to submit recommendations for amendments to the Draft Report that they believed would enhance the accuracy, logic, integrity and resilience of the Investigation Report. The following DIPs were invited to make submissions on the Draft Report:

- Alstom
- ALTRAC
- Construcciones y Auxiliar de Ferrocarriles (CAF)
- Office of the National Rail Safety Regulator (ONRSR)
- Transdev
- Transport for NSW.

Submissions were received from the following DIPs:

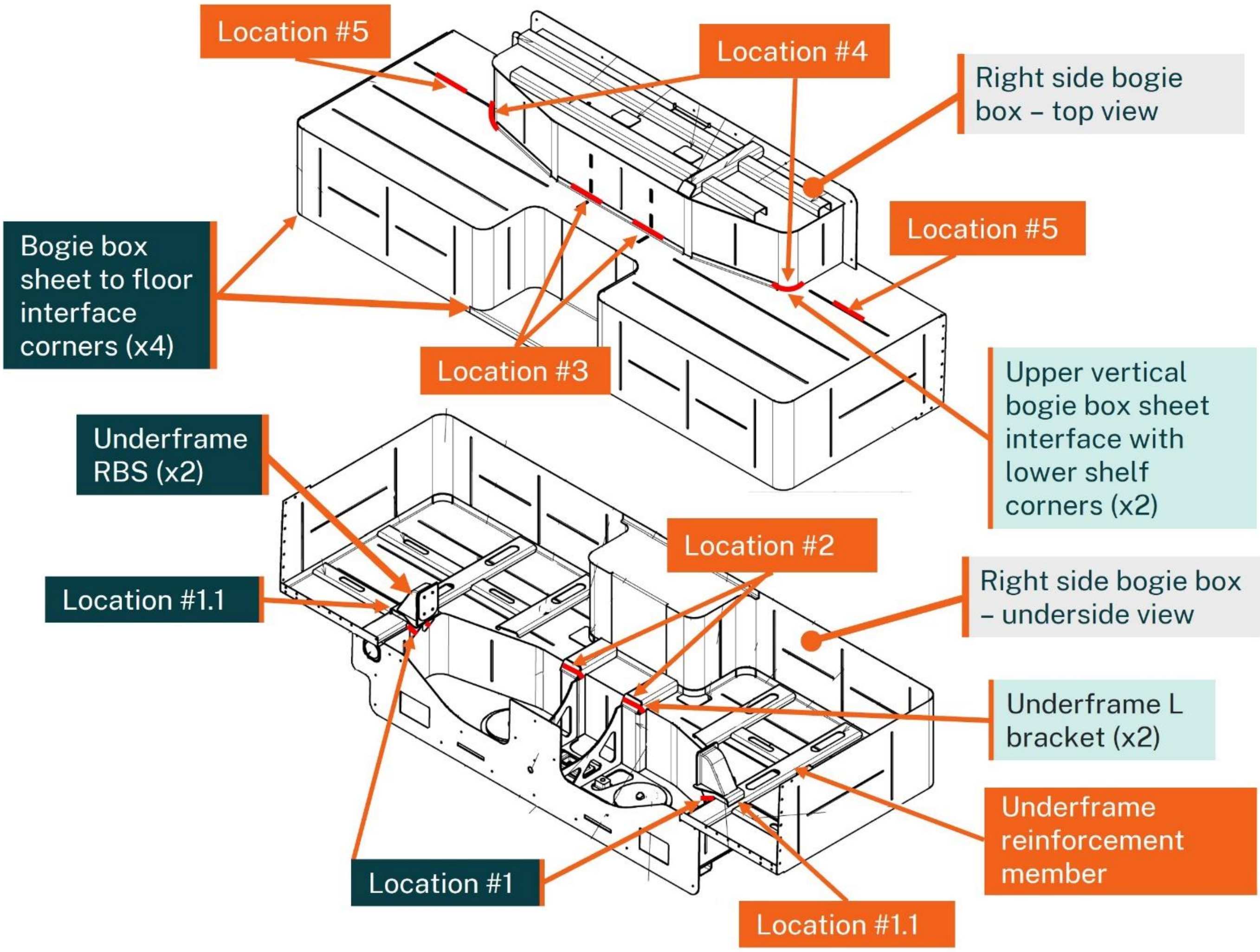
- ALTRAC
- Construcciones y Auxiliar de Ferrocarriles (CAF)
- Office of the National Rail Safety Regulator (ONRSR)
- Transdev
- Transport for NSW.

The Chief Investigator considered all representations made by DIPs and responded to the author of each of the submissions advising which of their recommended amendments would be incorporated in the final report, and those that would not. Where any recommended amendment was excluded, the reasons for doing so were explained.

Appendix 2: Urbos 3 fracture location data

Generic positions of the Urbos 3 fracture locations identified during post incident LRV inspections and their reference positions are depicted in Figure 34.

Figure 34: Underframe bogie box fracture locations

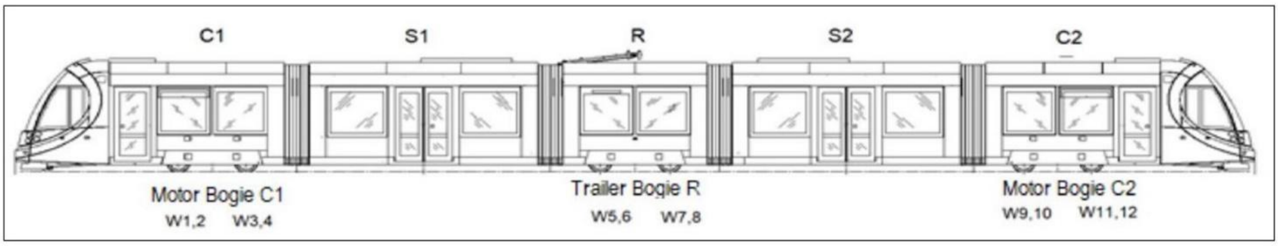


Top and inverted view of the right-side underframe bogie box assembly depicting typical fracture locations identified during visual and non-destructive testing. Fractures underneath the bogie box structure of the underframe were identified at Location #1 in the underframe RBS gusset, and Location #2 in the L bracket corner. Fractures on the top side of the bogie box structure were identified at; Location #3 in the bogie box sheeting interface between the upper vertical sheet and lower shelf, Location #4 in the upper vertical bogie box sheet with lower shelf corners, and Location #5 along the lower bogie box shelf sheeting. No fractures were identified in the horizontal welding of the RBS structure to the underframe reinforcement members at Location #1.1. Location #1.1 provided a reference location for the TfNSW design assessment review.
Source: CAF, annotated by OTSI

The fracture lengths at the various fracture locations were recorded, except for the underframe bump stop fracture measurements. The location of each fracture measurement for the individual units detailed in Figure 35 was referenced by the C module location (being either a C1 module or C2 module), fracture location number (being either #1, #2, #3, #4 or #5), the left or right bogie box side and the relevant wheel number for each bogie (being either W1, W2, W3…….W12). A summary of the fracture location details and some of their measurements are provided below:

- The top side fracture Location #3 was directly adjacent to the L bracket location #2 (Figure 34).
- The top side fracture Location #4 was directly adjacent to the RBS attachment to the underframe Location #1 (Figure 34).
- All C module underframe bogie boxes of the LRV fleet (48 in total) were identified with fractures in the L bracket location #2 (96 L brackets).
- Not all top side bogie box locations were identified with fractures, i.e. those locations depicted as location #3, #4 & #5.
- Not all underframe RBS had fractures in the underframe RBS gusset at fracture location #1, i.e. 35 per cent of C module underframe bump stop gussets were identified with fractures at location #1.
- Some examples existed of the C1 modules of LRV units U2112, U2116, U2118, U2121 with no underframe RBS fractures. However, those C1 modules had fractures at location #4 being in close proximity to the underframe RBS attachment at Location #1.
- Some examples existed of C1 modules of LRV U2112 at the W2 side bogie box and U2114 at the W2 side bogie box with no underframe RBS fractures (fracture location #1) and no topside fractures at Locations #3, #4 & #5.
- There were 4 bogie box sides where there were no fractures at either location #4 or location #5 together with no underframe RBS fractures at Location #1 (LRV U2112 W2, U2114 W2, U2120 W2 and U2121 W4 C1 modules).
- No fractures of the underframe RBS attachment to the underframe reinforcement member were detected at the horizontal and rear welds (Location #1.1).

Figure 35: Urbos 3 unit fracture locations, measurements and kms travelled



Module	Location	Wheel	U2112		U2114		U2115		U2116		U2117		U2118		Location	Wheel
		Kms	513694		503469		553961		571684		547083		560829			
C1	5	W1	0	0	0	0	0	0	0	0	40	0	80	60	5	W2
C1	4	W1	80	0	130	0	100	80	340	140	140	60	70	40	4	W2
C1	3	W1	100	0	130	0	210	0	20	80	200	150	340	240	3	W2
C1	3	W3	110	180	240	90	230	110	150	180	150	150	340	240	3	W4
C1	4	W3	100	80	140	80	130	80	140	150	160	110	40	0	4	W4
C1	5	W3	0	0	0	0	0	0	70	0	0	0	60	70	5	W4
C2	5	W9	0	110	50	340	0	0	60	330	0	360	100	230	5	W10
C2	4	W9	150	250	100	310	80	120	120	150	130	110	50	130	4	W10
C2	3	W9	130	210	50	150	120	260	270	340	270	310	300	350	3	W10
C2	3	W11	100	200	230	350	0	320	140	80	220	140	300	350	3	W12
C2	4	W11	60	150	120	450	130	300	20	100	160	90	50	60	4	W12
C2	5	W11	0	150	0	450	0	300	50	180	0	420	80	180	5	W12

Module	Location	Wheel	U2119		U2120		U2121		U2122		U2123		U2124		Location	Wheel
		Kms	531726		531860		512744		519014		386095		512342			
C1	5	W1	0	0	40	0	0	0	250	0	0	0	40	0	5	W2
C1	4	W1	120	60	80	0	100	50	200	100	120	85	110	100	4	W2
C1	3	W1	140	55	200	100	200	90	250	100	195	200	220	210	3	W2
C1	3	W3	220	160	230	100	220	120	240	150	210	170	220	180	3	W4
C1	4	W3	170	100	150	80	140	0	200	100	80	80	70	80	4	W4
C1	5	W3	0	0	0	0	0	0	200	0	0	0	70	0	5	W4
C2	5	W9	0	35	30	130	210	230	60	80	0	0	30	140	5	W10
C2	4	W9	165	120	110	180	90	150	120	200	70	130	120	140	4	W10
C2	3	W9	260	315	230	240	0	60	230	320	175	250	250	400	3	W10
C2	3	W11	115	315	230	200	230	240	230	310	220	240	240	220	3	W12
C2	4	W11	145	135	120	170	60	160	100	170	80	150	90	60	4	W12
C2	5	W11	0	45	0	40	0	0	90	370	0	110	80	340	5	W12

Legend

Fracture location #1 (underframe rotation bump stop (no dimension))

Fracture location #2 (L bracket fracture)

0 | 250 | 450 — Colour gradient of fracture lengths at Locations #3, #4 & #5 dimensions in mm

C1 denotes a power module C1
C2 denotes a power module C2
3 denotes fracture location #3 in bogie box
4 denotes fracture location #4 in bogie box
5 denotes fracture location #5 in bogie box
W# denotes the wheel position on an LRV bogie i.e, W1, W2, W3.......

Source: ALTRAC, CAF, OTSI tabulation

Appendix 3: Urbos 3 fracture detection timeline

Date	Activity
Apr 2018	Fractures were identified in the West Midlands Metro (Birmingham, United Kingdom) Urbos 3 Light Rail Vehicles (LRV) in the door portal area.
Q4 (Oct -Dec) 2019	Fractures in the underframe rotation bump stop (RBS) brackets and bogie box area were detected in the Birmingham Urbos 3 LRVs. Subsequent review, monitoring and investigations were undertaken into the fractures.
Feb 2020	CAF determined the root cause of underframe fractures in the Urbos 3 Birmingham fleet being due to bogie RBS contact loading with the underframe RBS. The factors determined to have contributed to that contact loading were identified as: • Tight curves[90] on the Birmingham network without suitable geometric transitions from straight track to the curved track, • Carbody underframe bump stop to the bogie rotation stop clearances being out of tolerance, and • LRV speed on the tight curves operating above acceptable track geometry design parameters.
May & Jun 2020	CAF undertook temporary repairs to the Birmingham Urbos 3 LRVs in the bogie box structure. The temporary repairs consisted of drilling holes at the end of fractures and riveting plates over the fractures to stop them increasing in size.
Q2 (Apr-Jun) 2021	CAF undertook further temporary repairs to the Birmingham Urbos 3 LRVs with welding of L brackets that were identified with fractures. The Birmingham LRV fleet continued to operate with speed restrictions being applied on sections of track with no transition curves between straight track and curved track. An additional inspection regime was also implemented to check for fractures within the bogie box area. CAF advised West Midlands Metro the L bracket fractures were the most critical with welding permitted on the L bracket if there was at least 70 mm width of the L bracket corner being fracture free.
Apr 2021	Transdev requested CAF for advice on any additional action to be taken on the door portal fractures previously identified in the Birmingham Urbos 3 fleet.

90 Tight curves on the Birmingham LRV network were noted have a radius from 25 m to 50 m.

Date	Activity
26 May 2021	CAF carried out inspections of Sydney Urbos 3 LRV door portal and window areas to check for fractures. Results of those inspections did not identify any reportable defects.
11 Jun 2021	Birmingham Urbos 3 LRVs were suspended from service following the discovery of additional fractures in the bogie box area, including in vehicles that had undergone the temporary repairs.
14 Jun 2021	CAF advised TfNSW about the Urbos 3 Birmingham LRV fractures. CAF's communication gave advice that there should be no issue for the Sydney Urbos 3 LRVs 'as long as the infrastructure, operational and maintenance aspects remain as considered during design phase'. CAF also advised that the cause of the fractures in the Birmingham LRVs was a result of them being driven above design speed for turnouts and tight radii curves. Preventative measures were advised to have been put in place to manage the continued operation of the Birmingham LRVs.
15 Jun 2021	TfNSW provided ALTRAC, Transdev and Alstom with CAF's advice and also sought additional detail from CAF of the Birmingham Urbos 3 fractures.
15 Jun 2021	CAF provided advice of the Urbos 3 Birmingham fleet fractures to TfNSW's Newcastle Light Rail Operator and Maintainer (O&M) Keolis Downer.
16 Jun 2021	Newcastle Light Rail O&M Keolis Downer sought a technical report from CAF describing the fracture issue and also requested if any special inspections were required.
26 Jun 2021	CAF advised TfNSW the Birmingham fracture issue would not be a problem for the Sydney LRVs and undertook to give further details of how the Birmingham issue had been managed.
14 Sep 2021	TfNSW's Newcastle Light Rail O&M provided CAF with a reminder to supply further technical details of the Birmingham Urbos 3 fracture issue.
15 Sep 2021	CAF provided TfNSW with a technical presentation covering the results of their investigation into the Birmingham fractures restating their advice regarding the Sydney LRV fleet. The presentation focused on the information of: • Bogie RBS can make contact with the underframe resulting in structural damage to the underframe.

Date	Activity
	• Vehicles running at correct service speed with RBS clearances to standard do not produce concern with contact loading of the underframe. • An increase in-service speed on infrastructure with tight curves and no transitions into those curves can cause an increase in RBS loading. • A reference to the checking of bogie RBS wear contained within the CAF TMP procedure BOG-04-005 (1.93b. on page 43)
16 Sep 2021 to 1 Oct 2021	Transdev Urbos 3 Lilyfield depot closed due to a COVID outbreak with multiple staff required to isolate. Staff from Randwick depot were employed to carry out a revised general inspection process that included an inspection of the underframe as per the Technical Maintenance Plan (TMP). The majority of Randwick staff had not inspected Urbos 3 vehicles before having only worked on the Citadis X05 LRVs that were operated on the Sydney L2 and L3 light rail lines.
21 Sep 2021	CAF provided the same presentation of the Birmingham fractures to ALTRAC and Transdev.
27 Sep 2021	Alstom maintenance staff discovered fractures in a Sydney Urbos 3 underframe RBS bracket. The maintenance technician was originally from the Randwick depot and transferred to the Transdev Lilyfield depot from 16 September 2021 to carry out IS inspections during a COVID outbreak.
28 Sep 2021	ALTRAC carried out an initial risk assessment covering the risk of underframe fracture in the RBS. The results of that risk assessment concluded the underframe RBS was assessed to remain functional while there was a diagonal RBS without fracture or the horizontal attachment welds were intact. Operation of the Urbos 3 continued based on there being no fractures in the horizontal welding of the RBS attachment to underframe (refer to Figure 7 on page 17) with those welds including the potential fracture location #1.1. The risk assessment also recognised that an additional fracture inspection regime was to be implemented to regularly check the RBS area for any increase in fracture damage.
1 Oct 2021	ALTRAC management were made aware of the Sydney Urbos 3 discovered fractures in the evening of 1 October 2021.
2 Oct 2021	ALTRAC advised TfNSW of the discovered fractures in the morning of 2 October 2021. ALTRAC's advice included a presentation of the risks identified with operating the LRVs with underframe RBS

Date	Activity
	fractures. ALTRAC's supporting risk assessment was in draft as of 2 October 2021.
4 Oct 2021	ALTRAC advised TfNSW that additional LRV inspections revealed 10 of the 12 LRVs had some level of fractures in the underframe RBS brackets and that one LRV (U2116) would not return to service due to the fractures.
5 Oct 2021	ALTRAC provided TfNSW with the results of the risk assessment that covered continued operation of the LRVs. The risk assessment permitted LRV operations with the underframe RBS fractures. The ongoing operation was conditional on 2 LRV's being subject to 15-day underframe fracture inspections, followed by a whole fleet wide underframe fracture inspection at the 30 day mark.
7 Oct 2021	CAF technicians inspected 4 of the fractured LRVs identifying that 22 of the 32 RBS clearances measured outside the 14-16 mm RBS clearance tolerance.
18 Oct 2021 and 20 Oct 2021	CAF provided TfNSW with a set of recommended actions, including deeper investigation of the bogie boxes and the supporting L brackets, and sought data and information from ALTRAC as to the fracture lengths and track geometry. That information was sourced to determine the cause of the fractures and provide input into the development of a repair plan. The data and information were sent to CAF on 25-26 October for analysis.
27 Oct 2021	ALTRAC advised TfNSW that all 12 LRVs had fractures to some extent in the underframe RBS brackets and that 2 LRVs had been identified with top side bogie box fractures. The top side bogie box fractures were identified after removal of the interior seats. ALTRAC recommended to TfNSW suspension of the Urbos 3 fleet to allow for a fleetwide survey to be completed. The Sydney Urbos 3 Fleet was subsequently suspended on 27 October 2021.
28-31 Oct 2021	The Sydney Urbos 3 LRVs underwent a fleet wide survey identifying fractures in the bogie box areas of all remaining LRV C Modules. The LRV fleet remained suspended from 31 October 2021 based on the complete inspection results.
8-12 Nov 2021	Some minor fractures were identified in the Sydney Urbos 3 LRV S Module window frame area, and C and R Module central window pillar following inspections conducted by CAF.

Date	Activity
13 Nov 2021	Transport for West Midlands (Birmingham) advised TfNSW the Birmingham Urbos 3 fleet was suspended due to accelerated propagation of fractures, including those with temporary repairs.
May 2022	A fleet wide inspection of the Sydney Urbos 3 R module bogie box was conducted and found all 12 Urbos had cracking of varying severity on the top plate of the R module bogie box. CAF proposed a temporary repair to allow the vehicles to return to service for a period of 12 months before the permanent repair was implemented. The temporary R module repair was conducted in parallel with the C module bogie box repairs and became an additional requirement for the Urbos 3's return to passenger service.
1 Aug 2022	Urbos 3 LRV units started to return to service after each unit had progressed through the repair and modification program.

Appendix 4: Urbos 3 static strain gauge testing 2012

In 2012 CAF completed Urbos 3 static carbody strain gauge testing with strain gauges to be installed at the highest stress points on the carbody structure. Placement of the strain gauges in the vicinity of the bogie box and underframe are detailed within Figure 36.

The strain gauges located closest to fracture locations #2, #3 and #4 included:

- location #2 relevant gauges IDs 9 & 10
- location #3 relevant gauges IDs 56, 93, 146, 149
- location #4 relevant gauges IDs 55.

Figure 36: Strain gauge placement locations for Urbos 3 static strain measurement

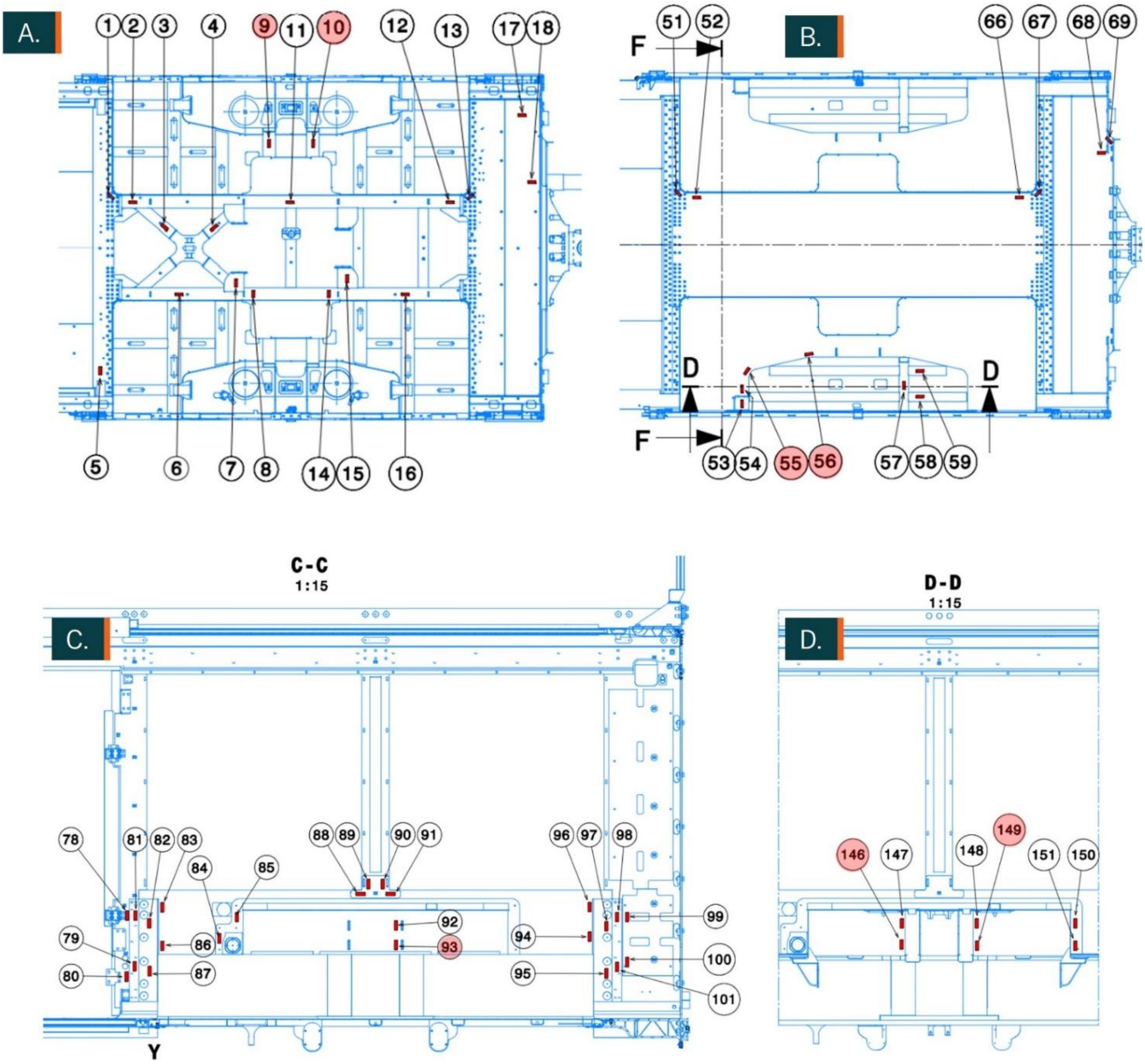


Figure A: Strain gauge positions of interest being 9 & 10, in proximity to fracture location #2,
Figure B: Strain gauge positions of interest being 55 & 56, in proximity to fracture locations #3 & #4.
Figure C: Strain gauge position of interest being 93, in proximity to fracture location #3,
Figure D: Strain gauge positions of interest being 146 & 149, in proximity to fracture location #3.
Source: CAF, annotated by OTSI

Vertical fatigue hypothesis results in MPa (N/mm^2) for the gauges positioned closest to the following OTSI fracture locations are detailed in Figure 37. The results were reviewed against the admissible MPa limits in the far-right column of Figure 37. The admissible MPa (N/mm^2) limits represent the applicable weld detail category selected by CAF to assess the hypothesis result.

Of note was the admissible limits for gauges 9, 10, 93, 146 and 149 selected as 103 MPa being the weld detail category of 'Base Material' as referenced in Figure 15 on page 30. Also of note was the admissible limits for gauges 55 and 56 selected as 51 MPa (weld detail category of 80 being an Angle welding 'T' discontinuous with force of longitudinal).

Figure 37: Strain gauge vertical fatigue results for Urbos 3 at selected gauge locations

APPENDIX A1.19 Vertical Fatigue

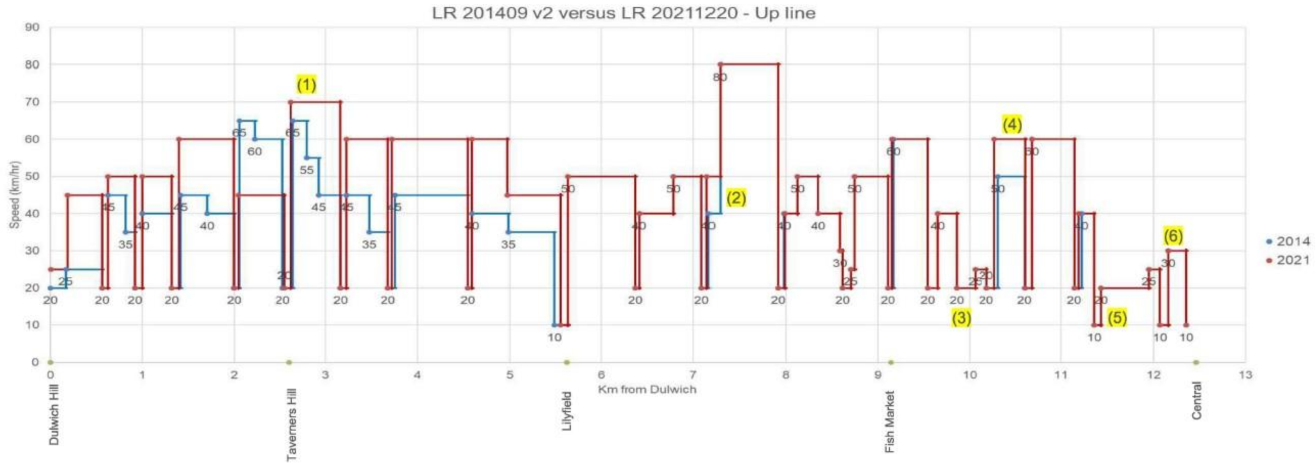
Gauge	Deformations		Hypothtesis range s/Ke	Δσ [Mpa]	
	80%	120%		hypothesis	admissibl e
1	-305	-426	120	8,4	56,9
2	-221	-298	77	16,1	103,0
3	-41	-31	10	2,1	103,0
4	-31	-42	11	2,2	103,0
5	5	15	10	0,7	56,9
6	-29	-40	10	2,1	103,0
7	-6	-10	3	0,7	103,0
8	6	6	0	0,1	103,0
9	-257	-370	112	23,5	103,0
10	-306	-417	110	23,2	103,0
52	37	25	12	2,6	51,0
53	-2	-5	3	0,7	103,0
54	107	142	35	7,4	51,0
55	533	703	169	35,4	51,0
56	108	69	38	8,0	51,0
57	309	479	169	35,5	103,0
58	120	181	60	12,6	103,0
59	294	424	129	27,1	103,0
92	66	88	22	4,6	103,0
93	213	287	73	15,4	103,0
146	342	508	165	34,7	103,0
147	-35	-53	18	3,7	103,0
148	-38	-53	16	3,3	103,0
149	223	305	81	17,0	103,0

Source: CAF, annotated by OTSI

Appendix 5: TfNSW IWLR line posted speed review 2014-2021

TfNSW noted some speed limits had been increased at locations on the IWLR line since the initial network design, however changes were not at locations where rotation bump stop (RBS) impact was likely to occur. That being track locations with tight radii curves and no transition curves adjoining those curves. A comparison of 2014 and 2021 network speed limits on the Up line is depicted in Figure 38, and the down line in Figure 39.

Figure 38: Historic IWLR Up line speed limit comparison



Up line speed limit comparison between 2014 and 2021 with TfNSW notes (1) to (6) detailed below providing additional commentary on the speed limits and the likelihood of RBS contact occurrence at those locations (Note Dulwich Hill referenced as zero track kms). Source: TfNSW

TfNSW observations from the Up Line Figure 38 included:

1. Increases in maximum operating speeds were seen at most sections between Dulwich Hill and Lilyfield. Curve radii within that section of track exceeded 150 m for all locations where change had occurred. It was not expected RBS stop impacts could occur, regardless of LRV velocity.

2. Speed limit increase from 40 km/h to 50 km/h occurred following Jubilee Park station before curve U10, with a minimum curve radius of 130 m. RBS contact was not considered at risk of occurring at this location.

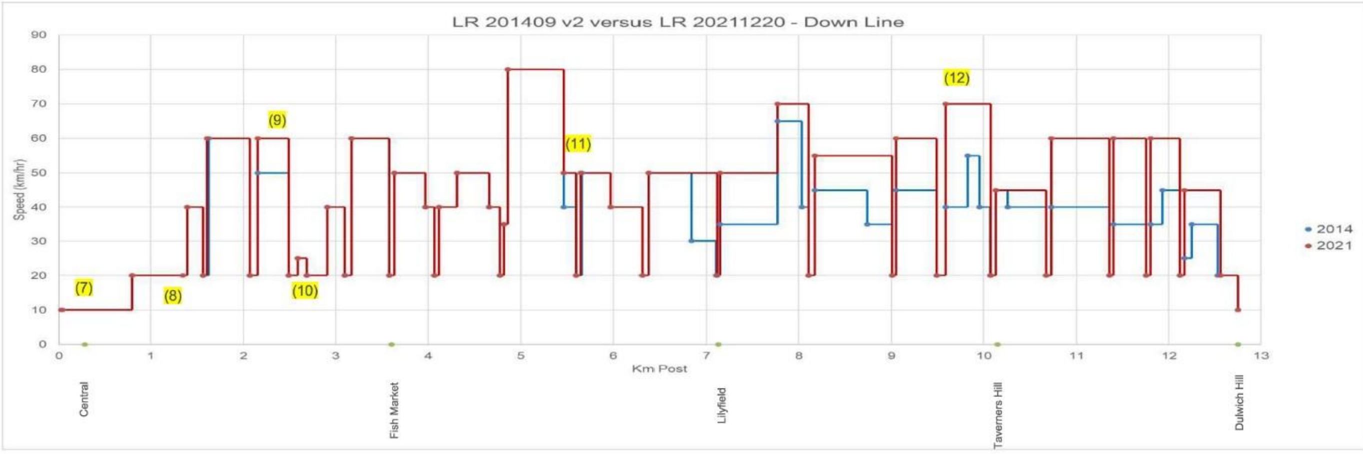
3. Curve U23 (2.849 km from Central, 9.857km on Figure 38 was the second tightest curve on the IWLR up track (69 m radius) outside of the central station turning circle. Speed limit had not been increased since the network design.

4. Speed limit increased from 50 km/h to 60 km/h occurred before curve U19/U20, with a minimum curve radius of 130 m. RBS contact was not considered at risk of occurring at this location.

5. Curve U14 (1.351 km from Central, 11.39 km on Figure 38 was the tightest curve on the IWLR up track (42 m radius) outside of the central station loop. Speed limit had not been increased since network design. No other curves outside of the central station loop had a curve radius less than 100 m.

6. Speed limit through the Central Station loop was unchanged since design.

Figure 39: Historic IWLR Down line speed limit comparison



Down line speed limit comparison between 2014 and 2021 with TfNSW notes (7) to (12) detailed below providing additional commentary on the speed limits and the likelihood of RBS contact occurrence at those locations (Note Central referenced as zero track kms).
Source: TfNSW

TfNSW observations from the Down Line Figure 39 included:

7. Speed limit through the Central Station loop was unchanged since design.

8. Curve D6 (1.351 km) was the tightest curve on the IWLR down track (47 m radius) outside of the central station loop. Speed limit had not been increased since network design.

9. Speed limit increase from 50 km/h to 60 km/h following Convention Station, minimum radius in the section was 136 m. RBS contact was not considered at risk of occurring at this location.

10. Curve D15 (2.846 km) was the second tightest curve on the IWLR down track (69 m radius) outside of the Central Station turning circle. Speed limit had not been increased since network design.

11. Speed limit increase from 40 km/h to 50 km/h, minimum curve radius in section of 190 m. RBS contact was not considered at risk of occurring at this location.

12. As per up-track, increases in speed was identified between Lilyfield and Dulwich Hill (Figure 38). The minimum curve radius in which a speed increase had occurred was 195 m. RBS impacts were not considered to be possible to occur in that section, regardless of LRV velocity.

Appendix 6: Underframe cumulative fatigue damage results

Dynamic testing carried out by CAF and TfNSW of the original and modified designs calculated cumulative fatigue damage within the bogie box area at strategic strain gauge locations. The calculation of those results were used to compare against cumulative fatigue limits of the design standard.[91] The CAF original design testing results were obtained from a vehicle with fractures present in the underframe, with any comparison of the modified design results providing indicative tendencies only. The results of that testing identified the following observations when compared against the respective OTSI fracture locations:

Fracture location #1: The cumulative fatigue damage results for both the original and modified design against weld category 36 were both below 1 with those results meeting the fatigue standard for a 30-year life.

Location #1.1: The cumulative fatigue damage result for the original design was below 1 against weld category 36 which met the fatigue standard for a 30-year life.

Fracture location #2: The cumulative fatigue damage result for the original design was below 1 against weld category 80 which met the fatigue standard for a 30-year life but above 1 against weld category 36 which did not meet the fatigue standard for a 30-year life. OTSI noted the difference in cumulative damage result between the 2 weld categories of 80 and 36, with the weld category 80 producing a less onerous cumulative fatigue damage result. Cumulative fatigue damage for the modified design was below 1 against weld category 71 which met the fatigue standard for a 30-year life. The change in weld category was due to the change in fabrication at that location, and noting the weld category 71 being a full penetration weld with force acting in the transverse direction.

Fracture location #3: The cumulative fatigue damage result for the original design against weld category 80 was above 1 which did not meet the fatigue standard for a 30-year life. The cumulative fatigue damage at multiple points were below 1 on the modified design against weld category 71 and weld category 36 which met the fatigue standard for a 30-year life with both of the weld categories assessing force in the transverse direction.

Fracture location #4: The cumulative fatigue damage result for the original design was below 1 against weld category 80 which met the fatigue standard for a 30-year life but above 1 against weld category 36 which did not meet the fatigue standard for a 30-year life. Cumulative fatigue damage for the modified design was below 1 against weld category 71 which met the fatigue standard for a 30-year life.

Fracture location #5: There were no strain gauge measurements applied in the vicinity of fracture location #5 to assess cumulative fatigue damage.

Details of the CAF and TfNSW cumulative fatigue damage results of the original and modified designs for; OTSI fracture locations, corresponding strain gauge locations and weld categories are provided in Table 5 and Table 6.

Table 5 identifies OTSI fracture locations (Figure 40) against CAF strain gauge location numbers with reference to the original design (Figure 41) and the modified design (Figure 42 and Figure 43). Red values identify where the ratio exceeded the cumulative 30-year fatigue assessment. Green values identify the ratio below 1 that met the cumulative 30-year fatigue assessment.

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[91] EN 12663-1 Structural requirements of railway vehicle bodies Part 1 (the EN 12663 design standard)

Table 5: Original and modified Urbos 3 designs - CAF bogie box cumulative fatigue damage

OTSI fracture Location	Original design			Modified design		
	Original Design Gauge location	Weld Category	Cumulative Damage	Modified Design Gauge location	Weld Category	Cumulative Damage
#1	44	36	0.15	47	36	<0.01
#1.1	43	36	<0.01	N/A		
#2	09C	80	0.43	55	71	0.07
		36	>10			
	11C	80	0.62			
		36	>10			
#3	48	80	>10	12	71	<0.01
		36	>10			
	49	80	2.06	13	71	<0.01
		36	>10			
				30	36	<0.01
				33	36	<0.01
				31	71	0.33
				34	71	0.42
#4	50	80	0.87	18	71	<0.01
		36	>10			
	51	80	0.24	20	71	<0.01
		36	>10			
#5	N/A			N/A		

Source: CAF

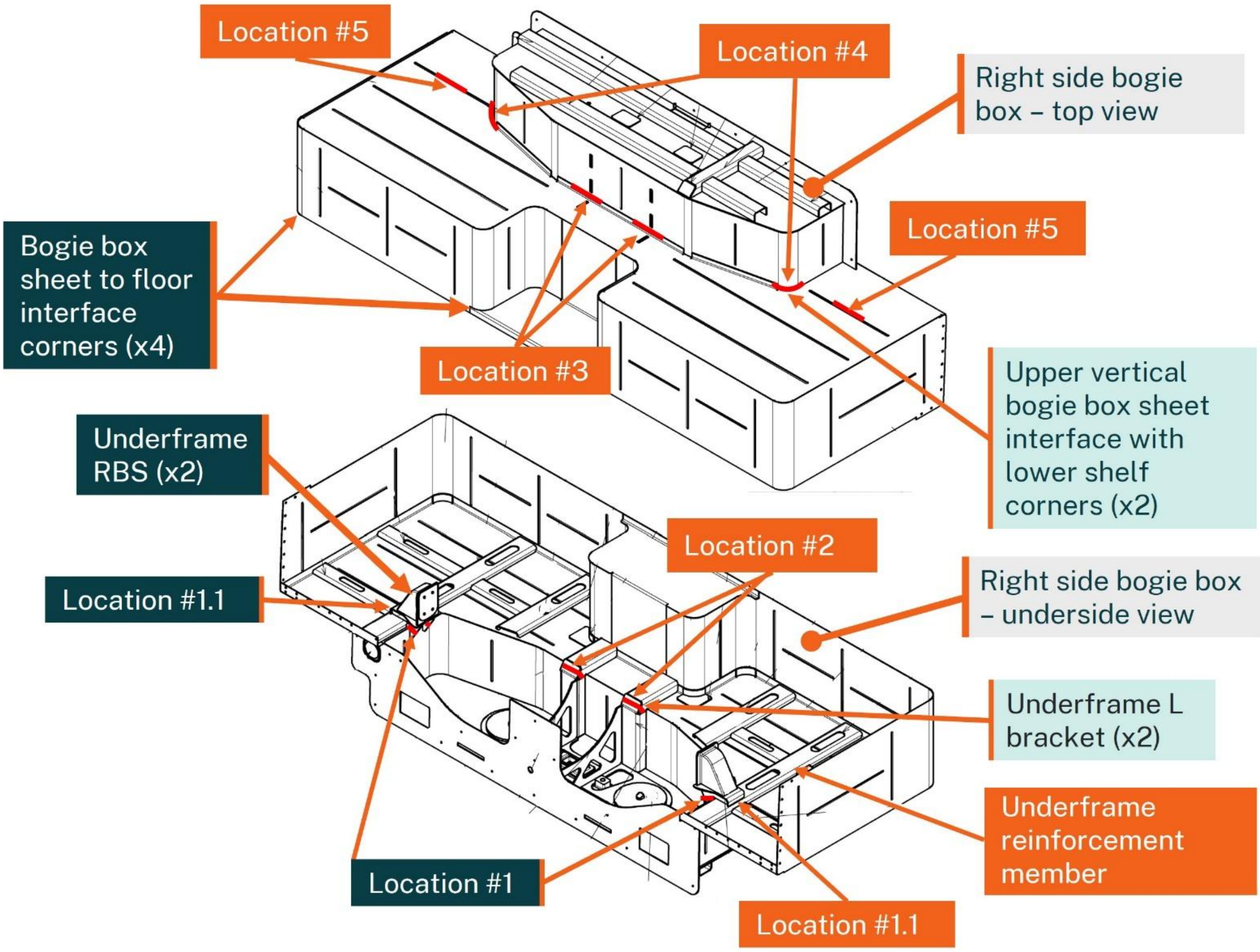
Table 6 identifies OTSI fracture locations against TfNSW strain gauge location numbers with reference to the original design and modified design (Figure 44 and Figure 45). Green values identify the ratio below 1 that met the cumulative 30-year fatigue assessment.

Table 6: Original and modified Urbos 3 designs - TfNSW bogie box cumulative fatigue damage

OTSI fracture Location	Original design			Modified design		
	Original Design Gauge location	Weld Category	Cumulative Damage	Modified Design Gauge location	Weld Category	Cumulative Damage
#1	Turning Stop Wheel 1	36	<0.01	N/A		
#1.1	N/A			N/A		
#2	N/A			1F	71	<0.01
				2F	71	<0.01
				3A	71	<0.01
				10A	71	<0.01
				12F	71	<0.01
#3	N/A			6F	71	0.025
				7F	71	<0.01
				8F	71	<0.01
				9A	71	<0.01
#4	N/A			N/A		
#5	N/A			N/A		

Source: TfNSW

Figure 40: Underframe bogie box fracture locations

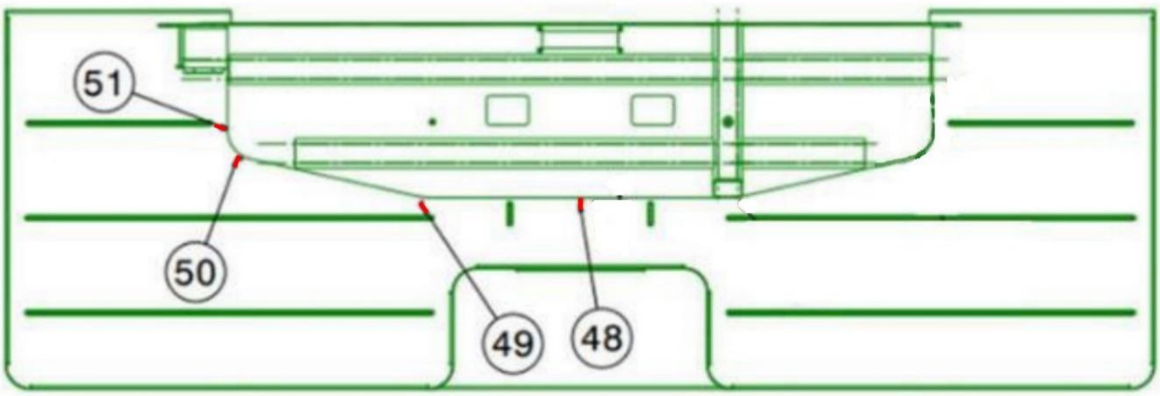


Source: CAF, annotated by OTSI

Original Design – CAF strain gauge placements

Figure 41: CAF bogie box strain gauge locations – original design

A.

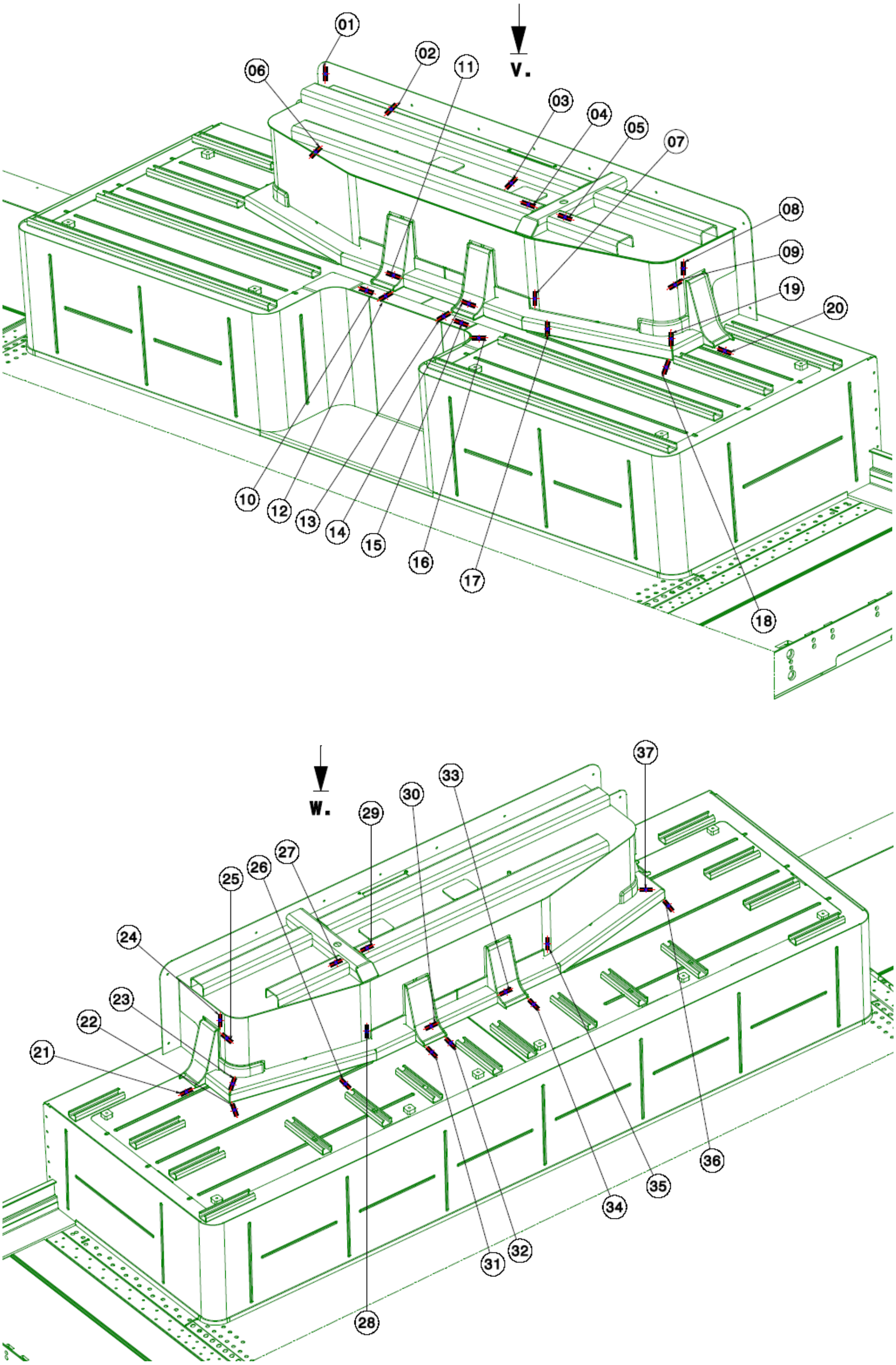


B.

Source: CAF, annotated by OTSI

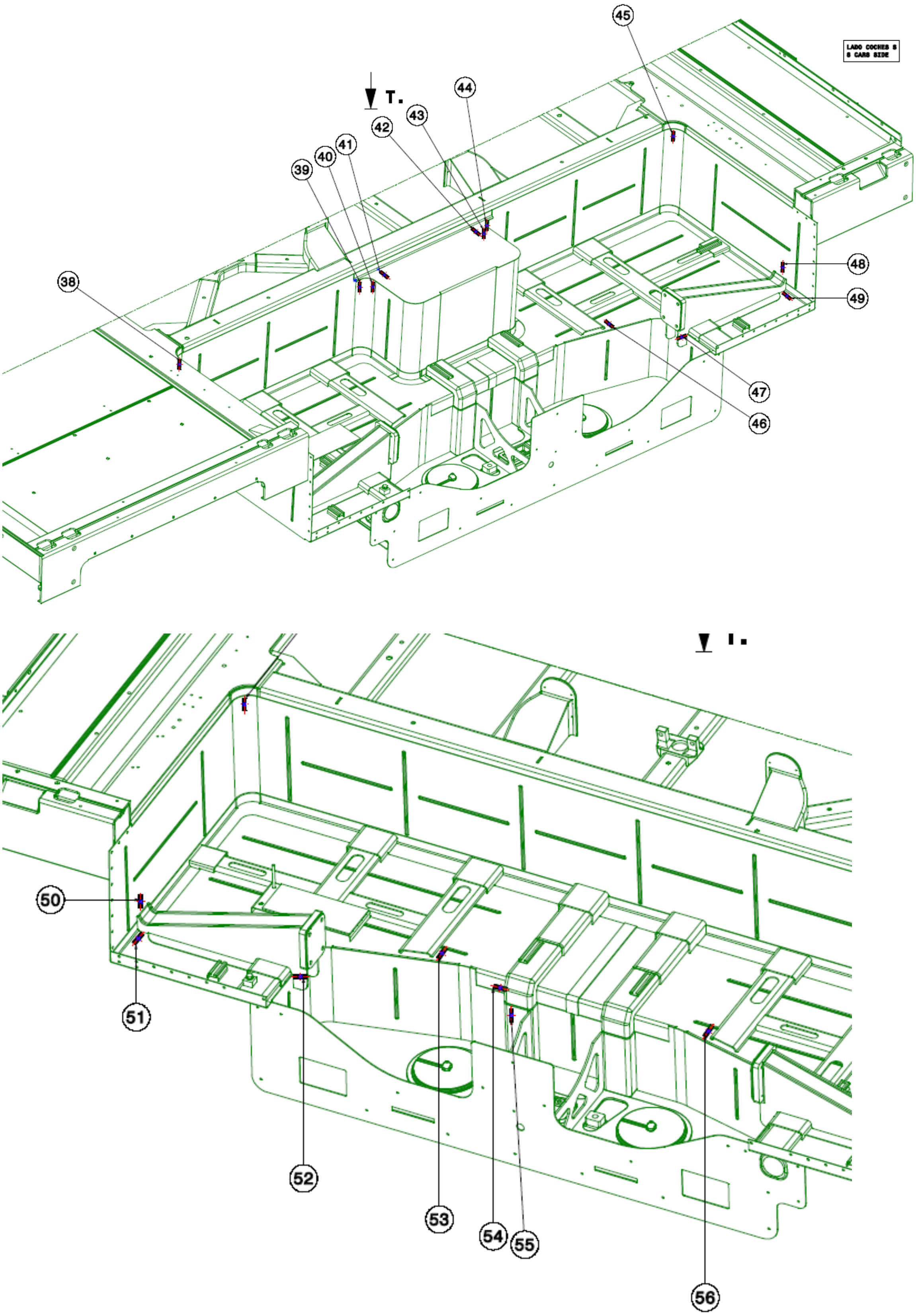
Modified Design – CAF strain gauge placements

Figure 42: CAF bogie box strain gauge locations – modified design top view



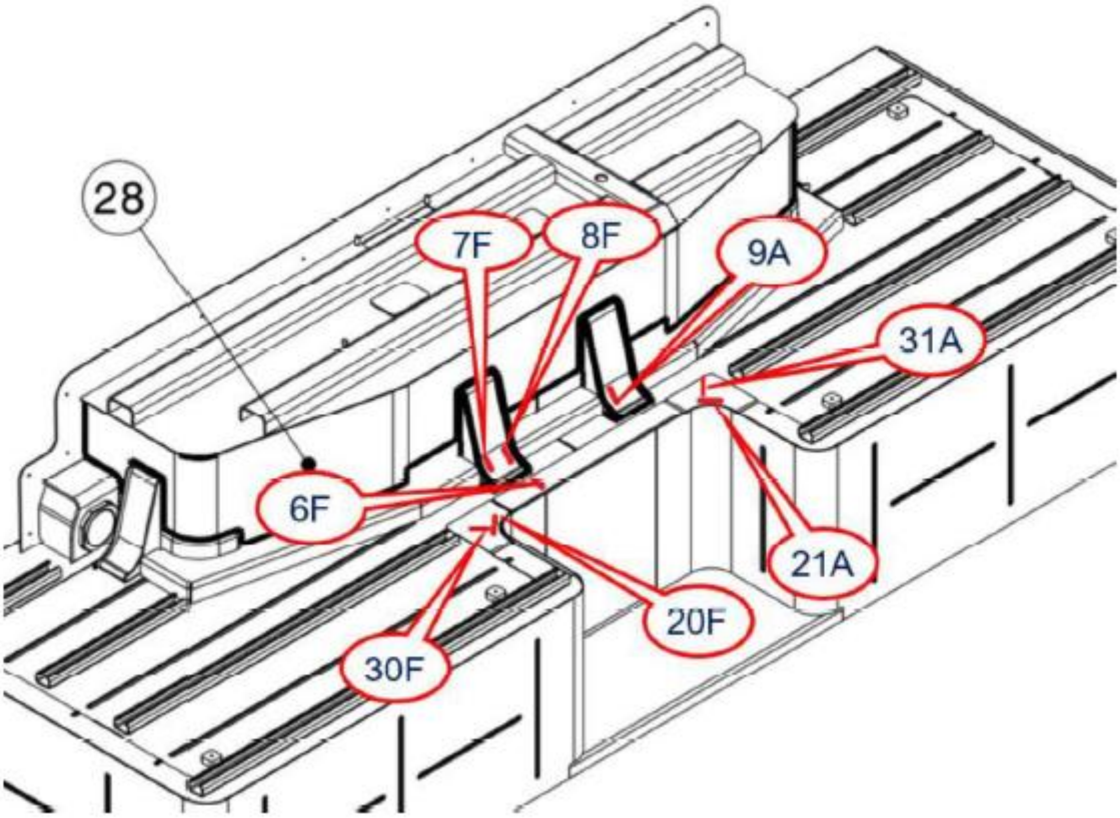
Source: CAF

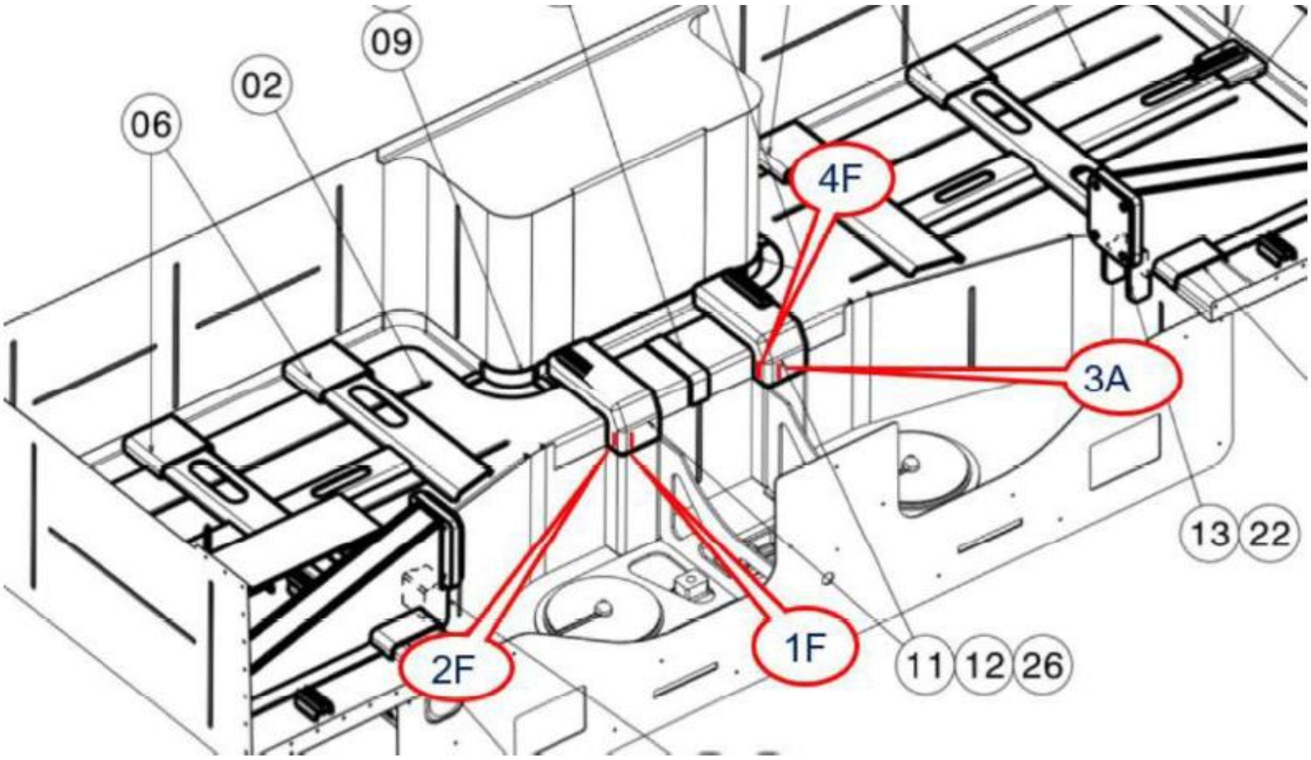
Figure 43: CAF bogie box strain gauge locations – modified design inverted view



Source: CAF

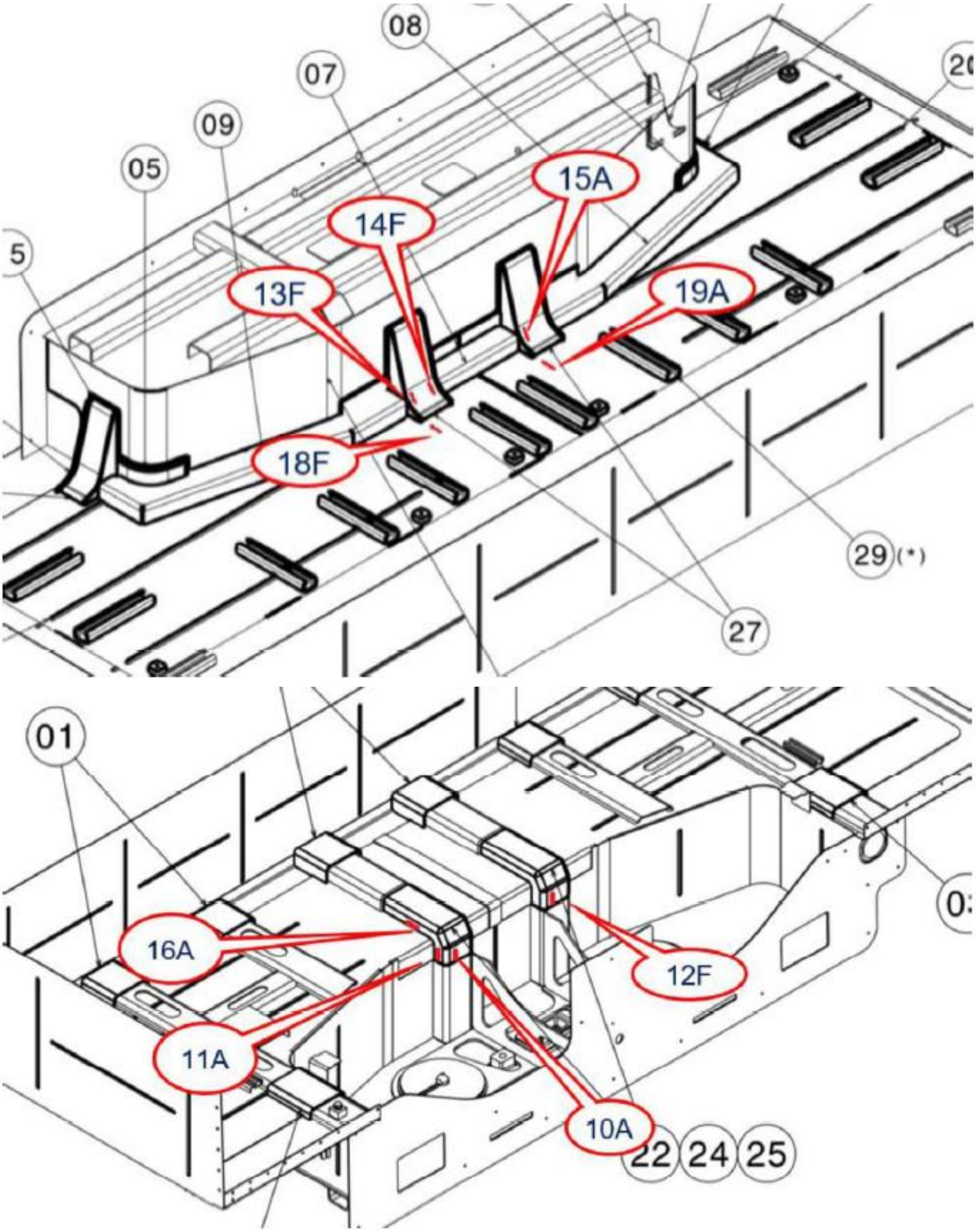
Figure 44: TfNSW bogie box strain gauge locations - modified design - RHS





Source: TfNSW

Figure 45: TfNSW bogie box strain gauge locations - modified design - LHS



Source: TfNSW

About the Office of Transport Safety Investigations

The Office of Transport Safety Investigations (OTSI) is the independent transport safety investigator for NSW.

The role of OTSI is to improve safety and enhance public confidence in the safety of the NSW transport network through:

- independent investigation of transport incidents and accidents
- identifying system-wide safety issues and their contributing factors
- sharing safety lessons and making recommendations or highlighting actions that transport operators, regulators and other stakeholders can take to improve the safety of bus, ferry and rail passenger and rail freight services.

OTSI is empowered under the *Transport Administration Act 1988* to investigate rail, bus, and ferry accidents and incidents in accordance with the provisions of the *Passenger Transport Act 1990* and *Marine Safety Act 1998*. It also conducts rail investigations under the provisions of the *Transport Safety Investigation Act 2003* (Cth) and a Collaboration Agreement with the Australian Transport Safety Bureau (ATSB).

The aim of an OTSI investigation is to enhance transport safety by sharing safety lessons and insights with those organisations that can implement actions to improve safety. OTSI uses a 'no-blame' approach to identify and understand contributing safety factors and underlying issues. It does not assign fault or determine liability in relation to the matters it investigates.

An OTSI investigation is independent of any investigation or inquiry that a regulator, NSW Police or the Coroner may undertake. While information gathered by OTSI in the conduct of its work is protected, the Chief Investigator, under the *Transport Administration Act 1988*, may disclose information if they think it is necessary for the safe operation of a transport service.

OTSI is not able to investigate all transport safety incidents and accidents or matters that are reported. The Chief Investigator focuses the agency's resources on those investigations considered most likely to enhance bus, ferry or rail safety by providing new safety lessons and insights that may be shared.

Many accidents result from individual human or technical errors which do not involve safety systems so investigating these in detail may not be justified. In such cases, OTSI will not generally attend the scene, conduct an in-depth investigation, or produce an extensive report.

OTSI may request additional information from operators or review their investigation reports which may lead to several activities, such as the release of a Safety Advisory or Alert to raise industry awareness of safety issues for action.

OTSI investigators normally seek to obtain information cooperatively when conducting an investigation. However, where it is necessary to do so, OTSI investigators may exercise statutory powers to conduct interviews, enter premises and examine and retain physical and documentary evidence.

Publication of the investigation report

OTSI produces a written report on every investigation for the Minister for Transport, as required under section 46BBA of the *Passenger Transport Act 1990*.

Investigation reports strive to reflect OTSI's balanced approach to the investigation, explaining what happened and why in a fair and unbiased manner. All Directly Involved Parties in the investigation are given the opportunity to comment on the draft investigation report.

The final investigation report will be provided to the Minister for tabling in both Houses of the NSW Parliament in accordance with section 46D of the *Passenger Transport Act 1990*. The Minister is required to table the report within 7 days of receiving it.

Following tabling, the report is published on the OTSI website — www.otsi.nsw.gov.au — and information on the safety lessons promoted to relevant stakeholders.

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