1 SCOPE

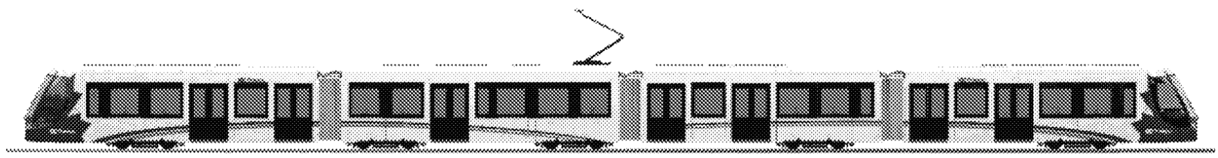
On 8th August 2021 at 20:16hrs, Ottawa LRV 1119 derailed approximately 110m after departing from Tunney's Pasture LRT station travelling in an Eastbound direction. The LRV eventually came to a stop approximately 165m after the derailment.

The purpose of this report is to document the investigation to the derailment and present the containment actions, root causes, and recommended next steps.

2 Description of the train

2.1 LRV overall summary

The Citadis Spirit LRV is a 100% low floor Light Rail Vehicle, consisting of 4 carbodies mounted on 5 bogies.



The LMC cars are equipped with motor bogies, the LCC car is equipped with one motor bogie and one trailer (non motorized) bogie and the IMC car is equipped with one trailer bogie.

The energy is taken from the catenary in the LCC Car. The current collection is made by one pantograph. The nominal voltage on the catenary is 1500 V.

Each LRV has a tare weight of roughly 81 tons with an overall length of slightly less than 50 meters. There are 120 passenger seats and 54 square meters of standing space for passengers.

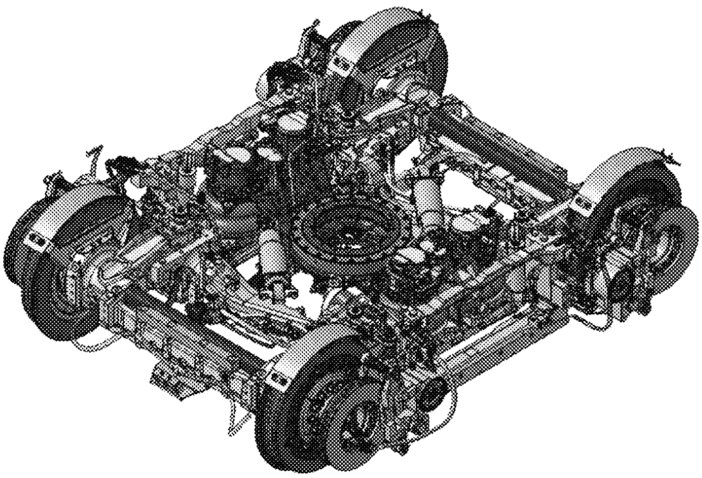
The service capacity of the system is based upon 3.3 passengers per square meter (300 total passengers per LRV) but dynamic performances are based upon passenger loading of AW3 (Assigned Weight of 6 passengers per square meter) or 444 passengers in total.

There is an operators cab in each end of the LRV.

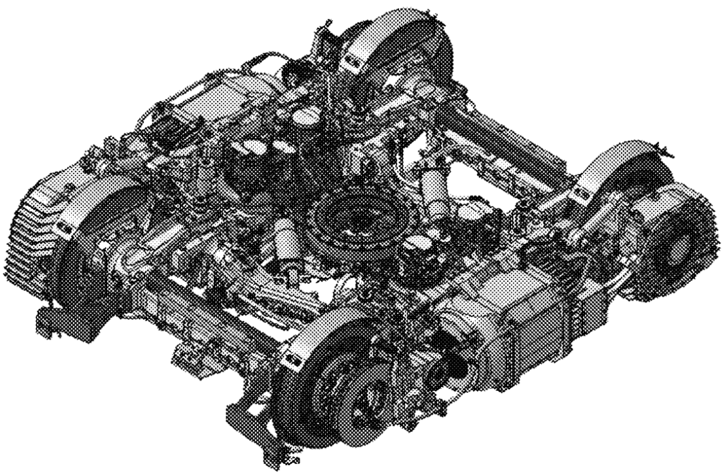
On the Ottawa alignment trains normally operate in multiple units of 2 LRVs.

2.2 Bogie overall summary

The motor bogie and trailer bogie are similar in overall arrangement, only differing by the equipment installed on each bogie



Trailer Bogie



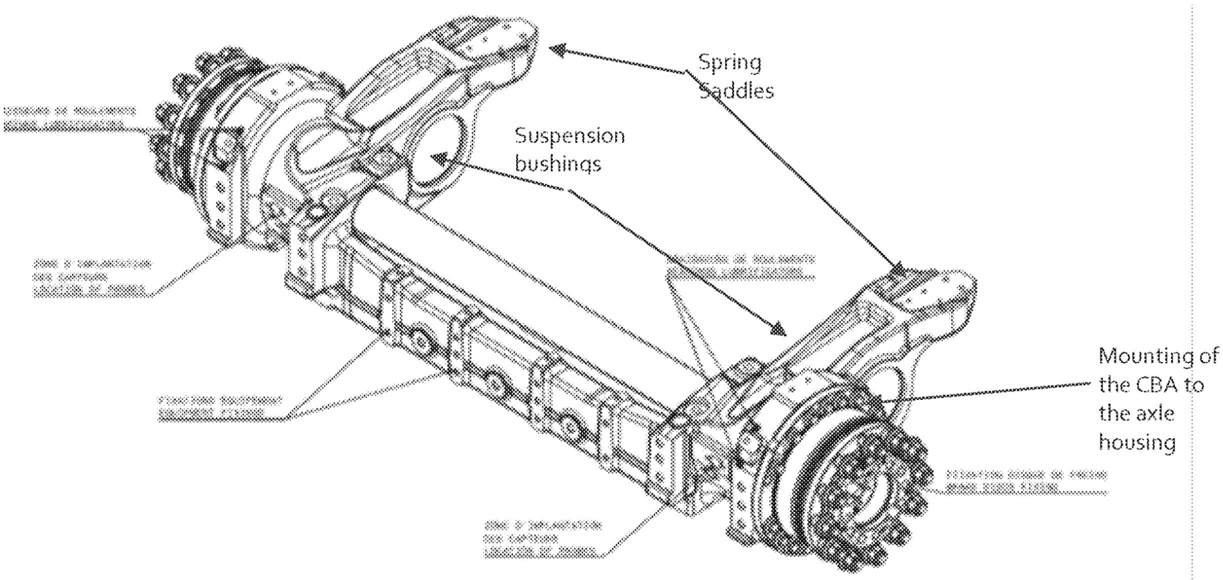
Motor Bogie

Each motor bogie has two traction motors and gear units, 1 track brake pair and one mechanical brake composed of 2 callipers and disks.

Each trailer bogie has 1 track brake pair and one mechanical brake composed of 4 callipers and disks.

All bogies have 2 axle assemblies and 4 wheels.

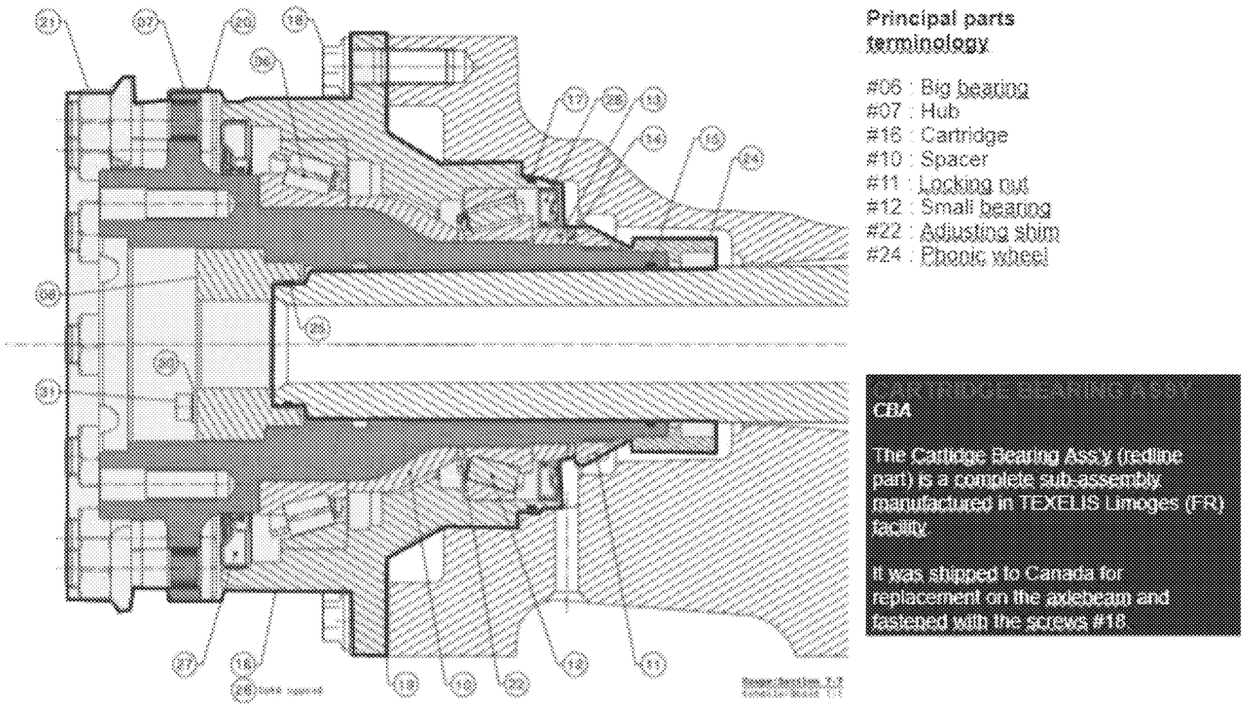
The axle assembly consists of an axle beam shown below that can pivot around suspension bushings mounted to the bogie frame. The axle load is countered by coil springs that react against the bogie frame under spring saddles that are on the opposite side of the suspension bushings from the axle



The hub and axle bearings are contained within a cartridge bearing assembly that is flange bolted to the axle housing.

The two hubs are connected by an 80mm diameter hollow shaft with splines on each end, that fit inside the hubs. The axle is not structural, and only provides a torque connection between the two wheels. Wear of the splines has been an issue due to the flexure of the axle beam, and the off axis rotation of the hubs relative to the axle. There was a retrofit of 100% of all CBAs beginning approximately January 2020 lasting almost 1 year, to replace the CBAs with ones that had a provision to allow regreasing of the spline without removal of the CBA.

The hub and cartridge bearing assembly is shown below



The complete axle beam is supplied by Alstom's subcontractor Texelis

In order to assemble the CBA, a trial fit up is made on the hub (item 7), of the bearings (items 6 and 12), spacer (item 10), to determine the thickness required for the shim (item 22) in order to have the bearing set to 0.0+/- 10µm. After disassembly and reassembly with the correct shim, the shaft seal seat (item 13) and thrust washer (item 14) are added, and the nut (item 11) is torqued to 2,000Nm. The design is that the preload on the nut is transferred through the path of the inner races and spacers and not on the bearings themselves.

3 INCIDENT OVERVIEW

3.1 Incident

On 8th August 2021 at 20:16hrs, Ottawa LRV 1119 derailed approximately 110m after departing from Tunney's Pasture LRT station travelling in an Eastbound direction. The LRV eventually came to a stop approximately 165m after the derailment. See Figure 1 below.

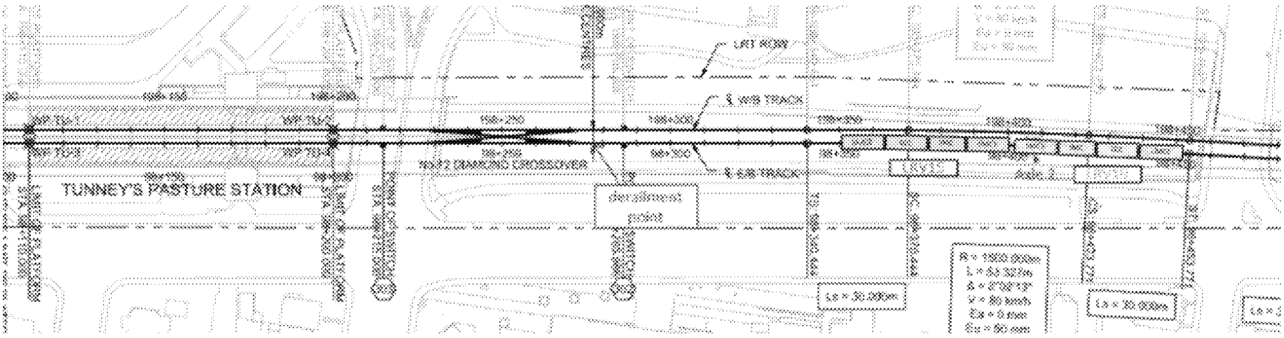
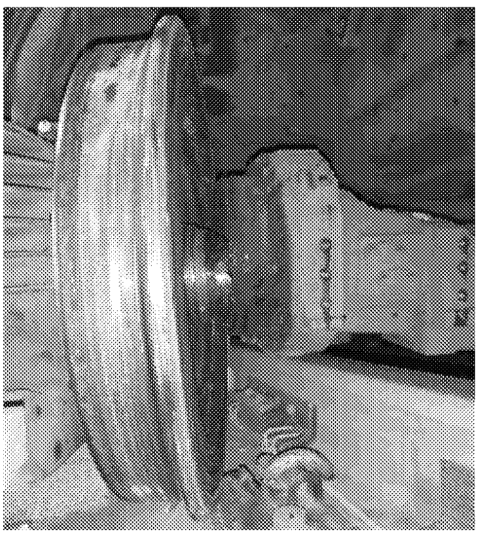


Figure 1 – Map of incident site

The move was an empty coaching stock move from Tunney's Pasture back to the Belfast Road Maintenance Facility. LRV 1119 was coupled to LRV 1115, with LRV 1119 leading in the direction of travel at the time of the derailment. Prior to departure for Belfast Road, the coupled unit had been stabled at Tunney's Pasture for 5 hours while awaiting guideway access permits to release a stuck brake on LRV 1115..

The Derailment occurred on No.2 Axle at the motor end, which was on the trailing bogie of 1119, and which was coupled to 1115.

The driver was notified that the train was trailing sparks after it departed Tunney's pasture, and brought the train to a stop, Upon investigation by the driver, it was discovered that the trailing bogie of LRV 119 had derailed. When the crew attempted to re-rail the bogie, it was discovered that the wheel on the motor end of axle 2 had become detached as can be seen in the photo below.



Pending initial review of the cause of this failure, and confirmation of the operational safety integrity at the time of derailment, the O-Train Citadis Spirit fleet was withdrawn from service. Service resumed once the conditions of the risk assessment (doc reference) were met.

3.2 Weather

There were no abnormal weather conditions at the time of derailment. The weather was dry with no precipitation. Temperature was around 23 degrees Celsius with a dew point of 20 degrees Celsius. The winds were east to east north east averaging 9-11 kph, It was mostly cloudy.

3.3 Track Condition

At the time of the derailment on August 8 there was one open work order against the track

Work Order Number	Detail	Date Opened
61065862	Wing of the frog 301 damaged	2021-08-04

From previous inspections in March 2021, The point of the switches in the affected area (SW301, SW302, SW303, SW304) showed signs of wear, however, the gauge was still within maintenance tolerances, and there were no work orders in the system for this observation.

As such, there were no defects present in the Tunneys's Pasture area that would lead directly to a derailment.

Other aspects with respect to the condition of the track are addressed under the investigation in section 5.

3.4 Train Condition

3.4.1 Train Condition at time of derailment

At the time of the derailment the consist was made up of LRV 1115 and LRV1119 with the #2 cab of LRV1119 being the active cab for east bound trips the #1 end of LRV 1119 was coupled to the number 1 end of LR1115.

There were no active faults, however, prior to the train being stabled at the westbound platform of Tunneys pasture, the train had exhibited a large number of sanding demands from MB1 of LRV1119 for spin and slide events.

- Train mode: ATO
- ATC Status
  - LRV1119 VOBC active
  - LRV1115 passive available,
- Brake status
  - Healthy on LRV 1119 No fault / One brake Cut out on LTV1115
- TCMS
  - Healthy/No faults
- Pneumatic systems: Healthy/Not in fault
- Traction braking systems: Healthy/Not in fault, LRV speed limit of 100 kph.

- EVR
  - Healthy/No faults

3.5 LRV Event Recorder Review

It is important to note that with respect to the train position in the EVR, in the east bound direction, the damaged axle was 42.75 meters from the nose of the train .

As a general note the consist was made up of LRV 15 and LRV19 with the #2 cab of LRV19 being the active cab for east bound trips

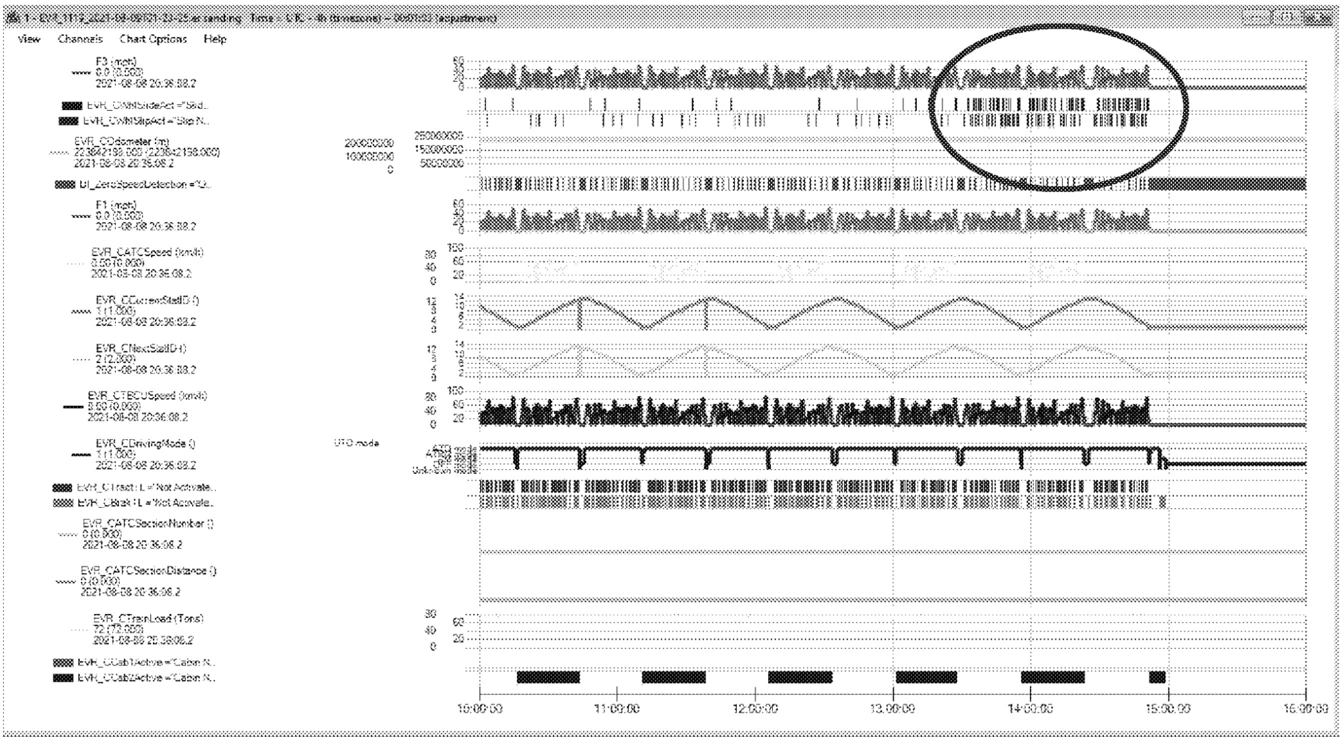
The #1 end of LRV 19 was coupled to the number 1 end of LR15

3.5.1 Snapshot review of the revenue service prior stopping the train at Tunney's

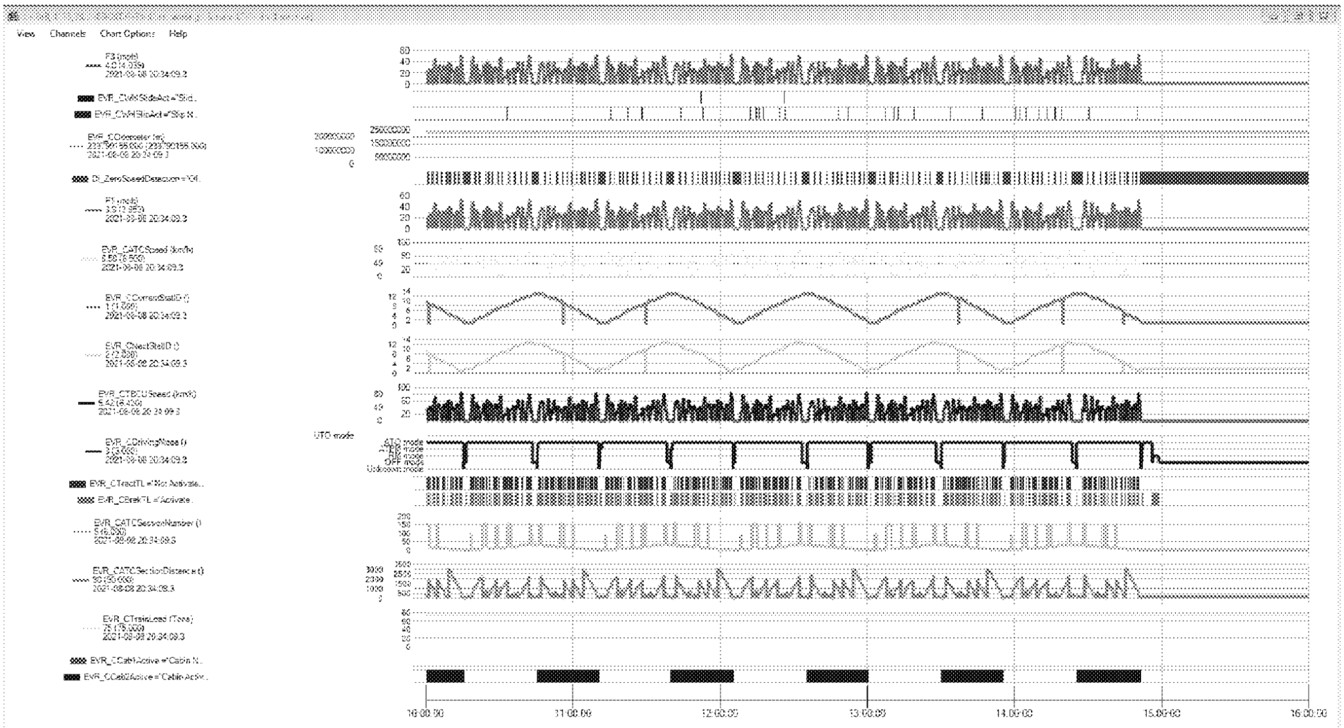
The train was launched at approximately 8:10 am and was sent westbound from the MSF to Tunneys.

The train completed 7 round trips by 14:50 when it was parked at Tunney's Pasture for a brake fault on LRV1115

Over this period the train operated at what appears for all purposes at a normal revenue speed profile with the exception that TS19 had an unusually high number of spin slide events especially in the final 90 minutes prior to parking the train at Tunneys. See the two Event Recorder charts below showing TS19 and TS15



TS19 EVR



TS15 EVR

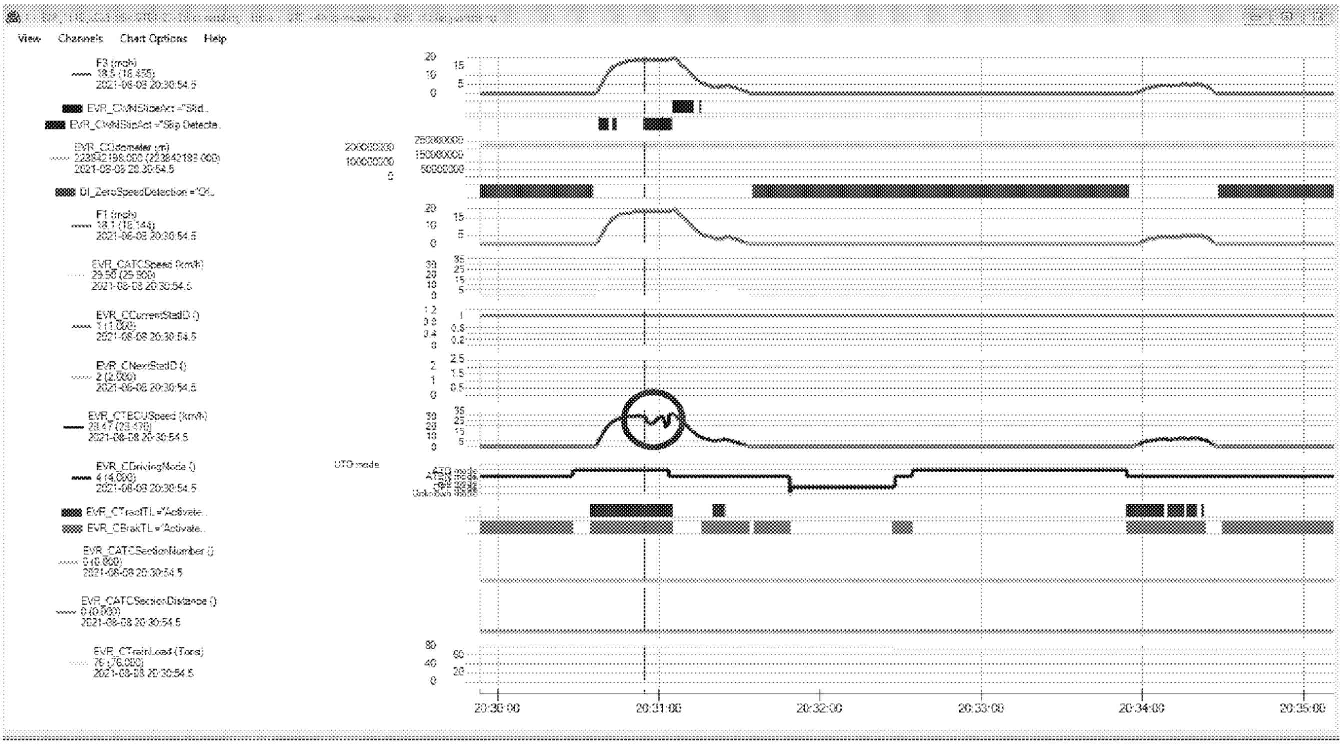
3.5.2 Maneuvering at the platform prior to the incident

The following sequence was observed during the process to isolate a dragging brake on LRV1115:

- Cab 2 of LRV 1119 was activated at roughly 20:07:29
- The train was moved in ATPM on the westbound track, east through switches 301 and 304 stopping 109 meters past switch 304
- The total distance of this move was 192 meters
- It appears the train then had a “Bump test” where it moved 5 meters further forward.
- The train was then reversed (cab 2 of LRV 1115 activated) and run back and stopped in normal docking position at the west bound platform

3.5.3 The incident

- The #2 cab of LRV 1119 was activated at 20:28:42
- ATO operation was selected at 20:30:28 and the train began to move at 20:30:35
- The train accelerated normally to 30 kph, although on TS19 there was a reported spin for most of the time accelerating.
- As the train transitioned from track 1 to track 2 through switch 301 and 302 the speed observed on TS19 by the TCMS became irregular, see Event Recorder trace below as this is the probable point of failure.

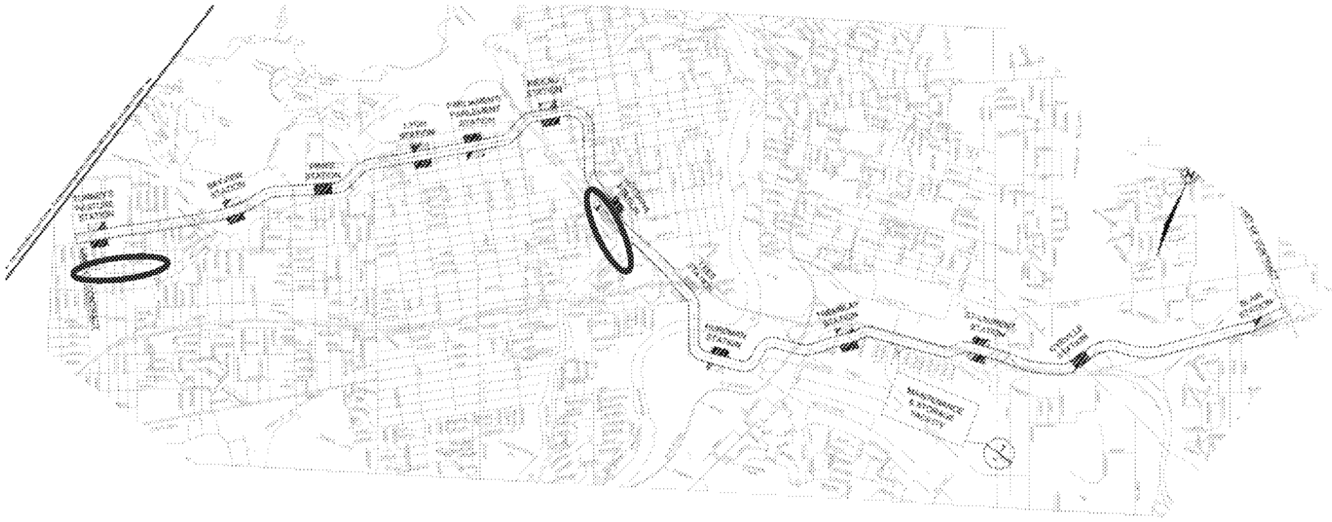


- At the point of disturbance in the TCMS speed, the nose of the train was 40 meters beyond the point of switch 302, meaning the axle that derailed was within 2.7 meters of exiting the switch. This is consistent with the marks observed on the switch, where the wheel is believed to have derailed / separated from the LRV.
- The train continued for an additional 9 seconds - 75 meters in ATO before the Operator moved the master controller to brake and stopped the train.
- The train came to a stop 165 meters beyond the time of derailment.
- After the train came to a stop, the operators on board changed ends and drove the train west bound for 49 meters at about 6.5 KPH before they came to a stop.

3.6 Parts found on the track.

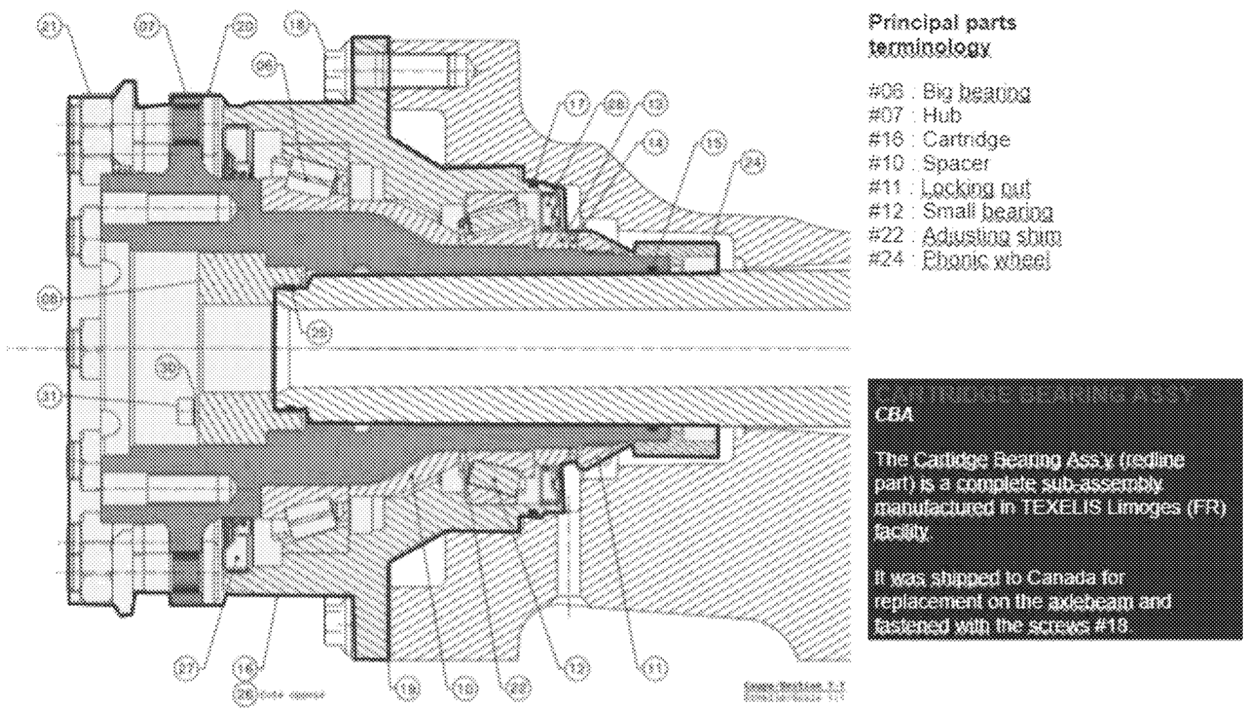
Following the incident, during the recovery process of the LRV, many of the internal parts of the bearing hub were found on the track. The discovery of the parts on the track was over several days.

Globally, parts were found in two known locations one at the derailment site, and the other location is in the vicinity of uOttawa station note that uOttawa is roughly 5 km away from the derailment site,



3.6.1 Axle components Found on the roadbed

The figure below represents the Axle hub Assembly and outlines the major parts of the assembly



Axle hub Assembly

The following parts, arranged somewhat in the order of assembly, are hub assembly parts that were found at the derailment site distributed along the east bound section of the track after switch 302

In this sequence of parts, the only parts unaccounted for are the spacer between the thrust washer and the bearing race which was subsequently found, and the rolling elements of the inner bearing. 9 of 19 were ultimately picked up at the derailment location. None of the rolling elements of the outer bearing were found at the derailment site. Ultimately 4 of the 30 rollers from the outer bearing were found at uOttawa and at switch 309

With reference to the illustration of the assembly above, the parts are, from right to left,

- The "phonic" wheel item 24,
- The bearing locking nut item 11,
- A thrust spacer item 14,
- Inner bearing item 12 (inner race only) ,
- the small diameter portion of the hub split in half which has no item number,
- bearing spacer (between the inner and outer bearing) item 10
- bearing rollers from the inner bearing (not shown in the photo)

In addition to the parts found on the track at the derailment location, attached to the wheel, is

- the remainder of the hub
- the inner race of the outer (large) bearing item 06

remaining with the axle housing on the bogie are

- the outer housing of the hub and bearing cartridge
- the outer race of the outer (large) bearing
- probably but not seen due to location in the assembly
  - the outer race of the inner bearing item 12
  - the inner shaft seal item 28
  - the outer seal (likely damaged) item 27

Parts found along the track while returning to the MSF

- Bearing rollers from the outer bearing
  - 3 at the fouling point of switch 309
  - One at uOttawa
- Bearing roller from the inner bearing
  - Location unknow
- The spacer and inner shaft seal (item 13)
  - Location unknown

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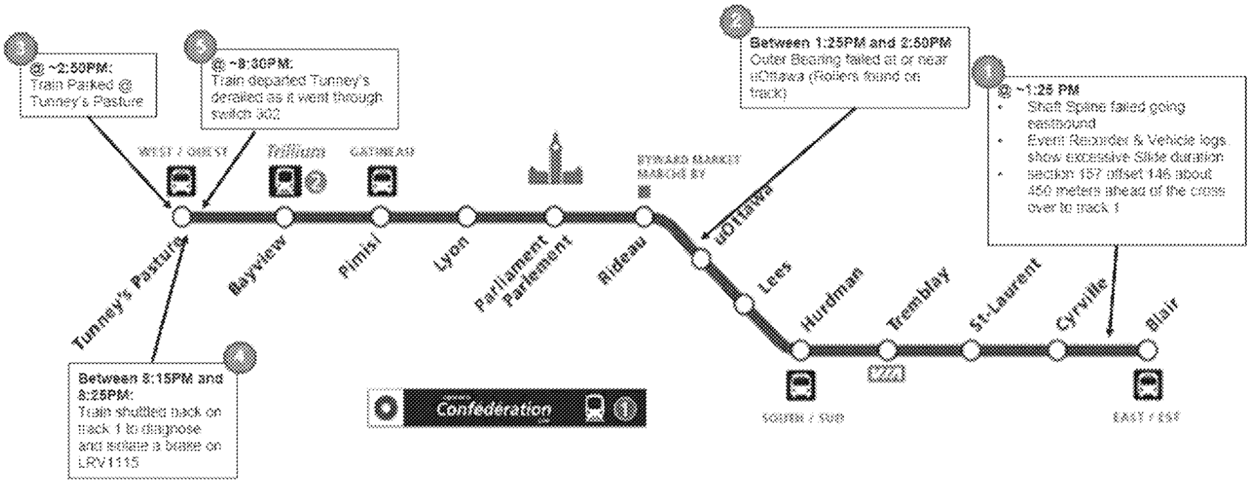
3.7 Summary of the operation considering parts found and event recorder.

As a summary, the significant points can be best illustrated on the commented system map below



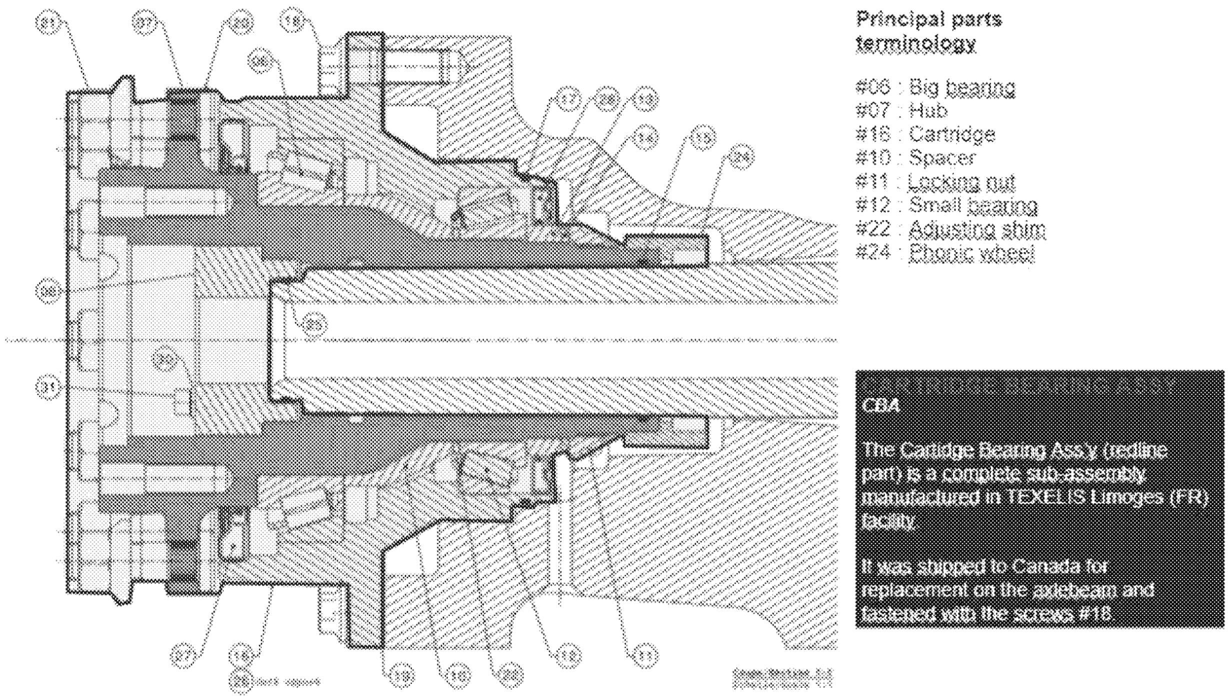
LRV19 Sequence of Events

4 Detailed investigation

The investigation focused on the failure of the hub assembly and therefore began with a review of the parts of the hub following the derailment.

4.1 Review of the individual parts

A cutaway of the axle hub is shown below.



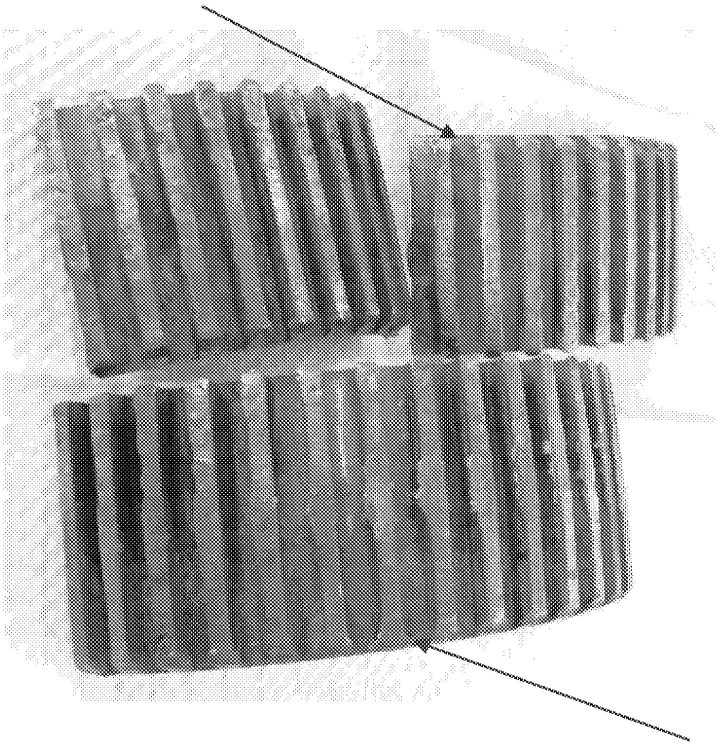
Axle hub Assembly

4.1.1 The "phonic" wheel item 24,

This part was found in 3 pieces between the derailment point and the resting position of the LRV.

It is interesting to note that the phonic wheel came in contact with a curved shoulder, likely the radiused back of the cartridge.

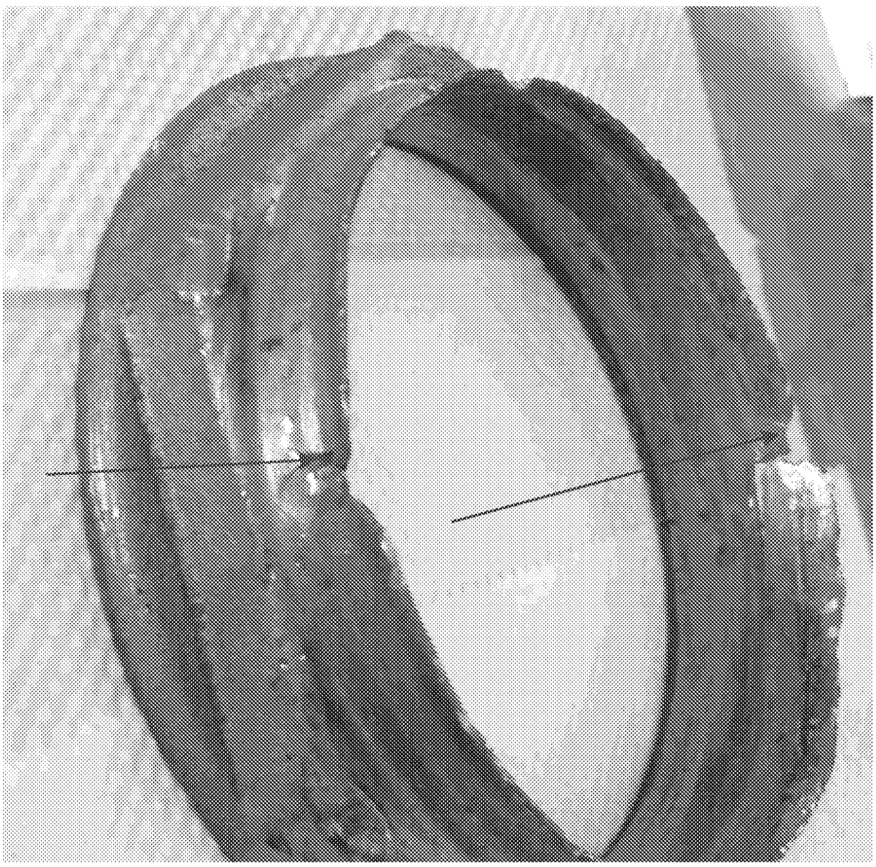
The areas indicated in the following figure, with the arrows suggest that the smearing was against a vertical surface. The back of the cartridge is the only such surface.



4.1.2 The bearing locking nut item 11,

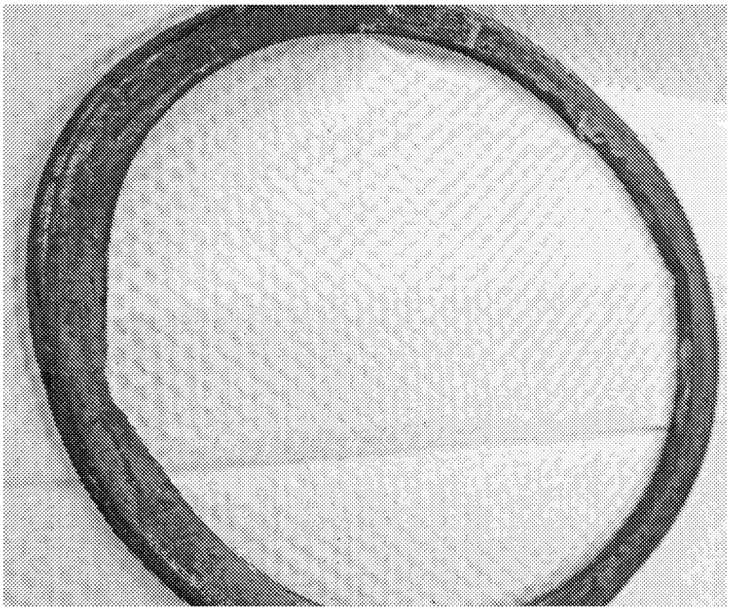
The lock nut has no evidence of threads internally, and has suffered from extreme heat as all the paint is burned off.

The two swage points can be seen where the arrows are located.

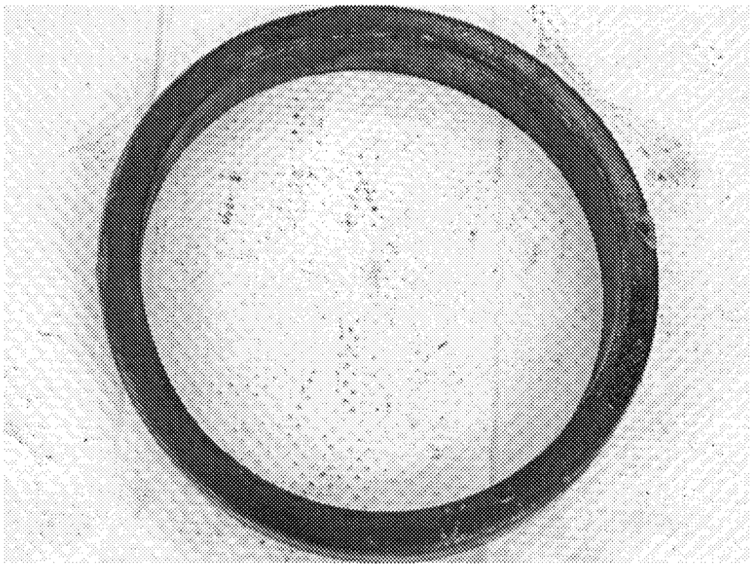


4.1.3 The thrust spacer item 14,

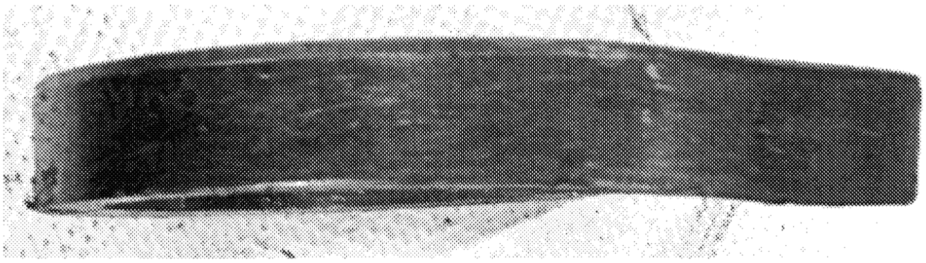
The anti rotation tabs that engage it in the hub are missing



4.1.4 The spacer and inner shaft seal (item 13)



Note that this part is bent, as shown in the photo below shot from the edge of the part

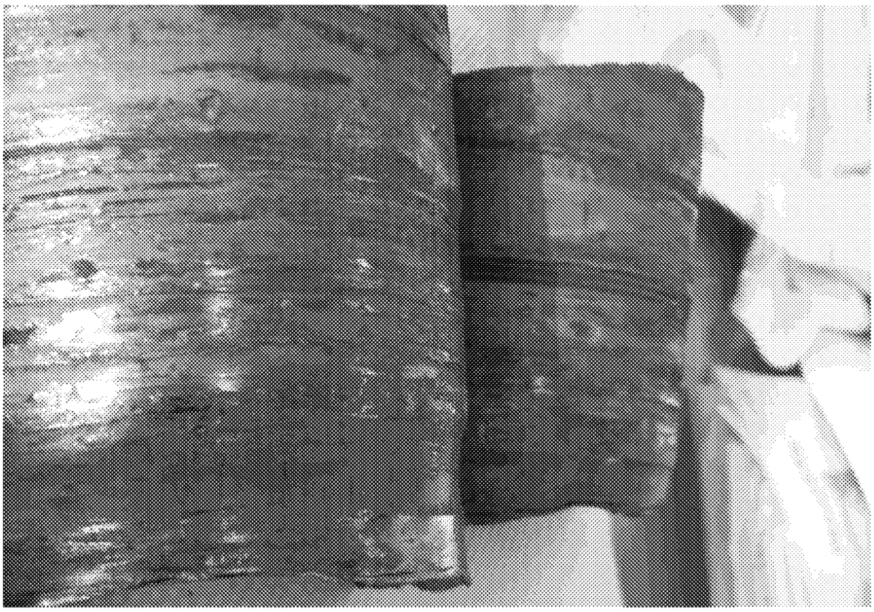


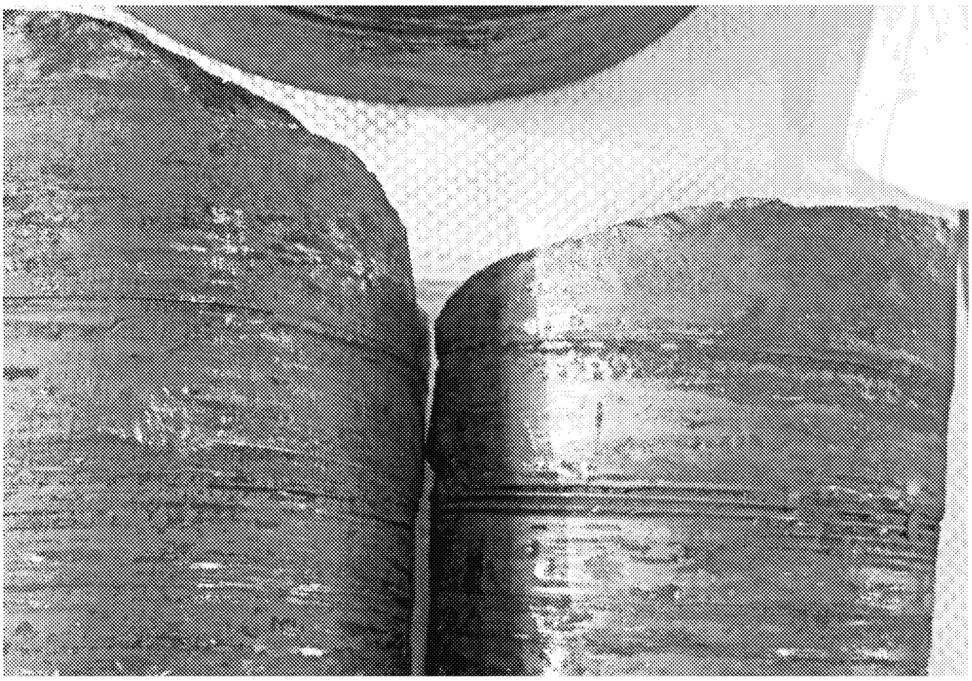
4.1.5 Inner bearing item 12 (inner race only) ,

Aside from the general shape being consistent and both shoulders present, there is not much that can be determined visually

4.1.6 The small diameter portion of the hub split in half which has no item number,

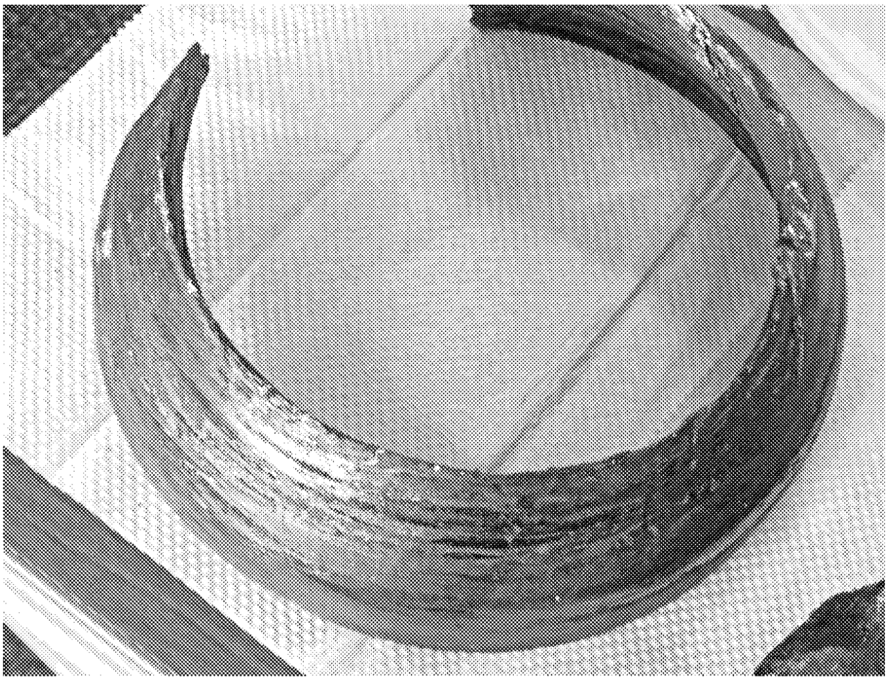
the hub shows some if not all of the threads for the lock nut. It may be that the threads are not necessarily lost, but filled with metal from other parts.





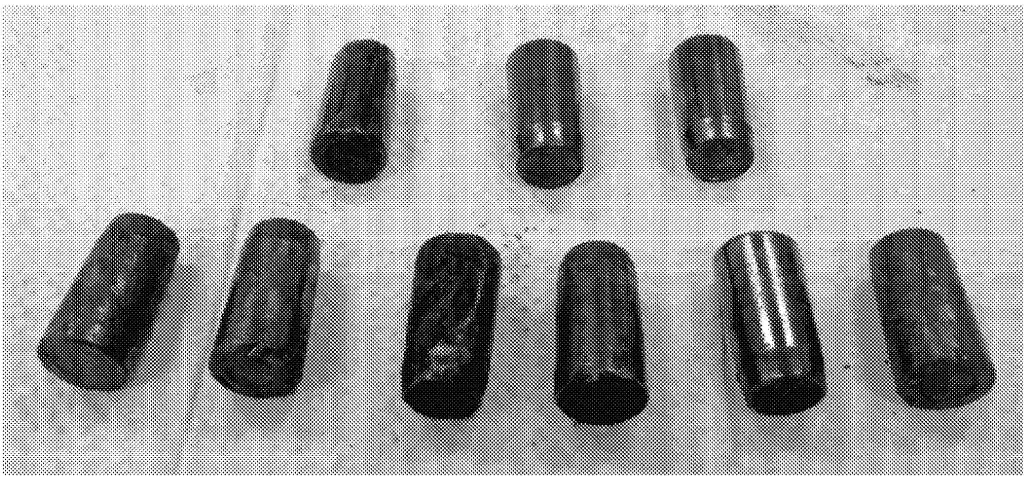
4.1.7 bearing spacer (between the inner and outer bearing) item 10

this part clearly was in hard contact with the cartridge housing. And would have been taking the main load of the axle when the bearing failed



4.1.8 Bearing rollers

The bearing rollers were found in two conditions, those found near the derailment site were blue/black in appearance, and with the exception of impact marks or obvious rubbing marks where the rollers were caught between moving parts, were in good condition.



9 rollers were found at the derailment site. These are all from the inner bearing

The photo below shows the best and worst case rollers.

The rollers found at the fouling point of switch 309 showed much more physical damage

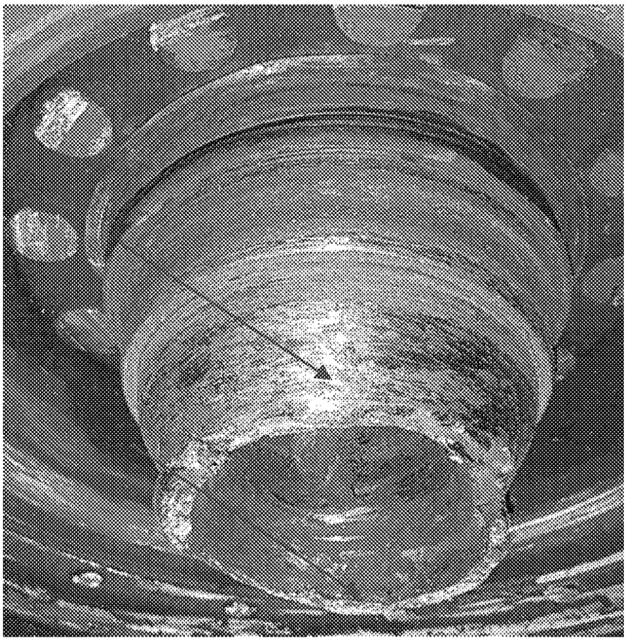
Note that these are all from the outer bearing. An additional bearing roller from the outer bearing was found at uOttawa. The rollers are shown below.

Three rollers found at switch 309

Regardless of location there does not appear to be any visual evidence of fatigue spalls .

4.1.9 The remainder of the hub and the inner race of the outer (large) bearing item 06

Both shoulders of the inner race are still present. There also appears to be a crack, see the red arrows below.

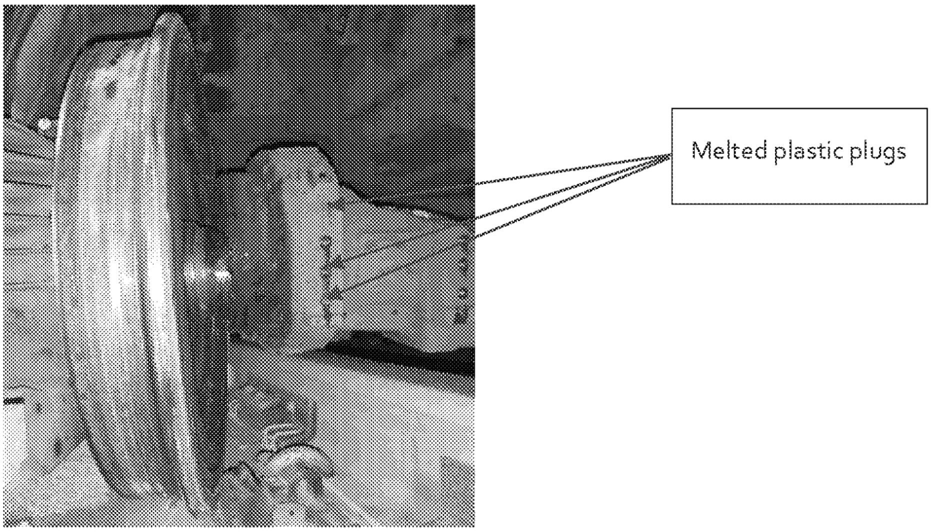


The outer housing of the hub and bearing cartridge and the outer race of the outer (large) bearing

A more detailed review would be required to make any assessment of the bearing race, however the high amount of rust may be the result of prolonged heat.

4.1.10 The axle beam

A review of the condition of the axle beam provides some additional interesting data.



It can be observed in the photo above that the plastic plugs inserted into the beam, have melted and dripped. These plugs melt at 110 degrees Centigrade and give an indication of the temperature of the outer housing.

4.1.11 Work to be done on TS19 parts moving forward

- Dimensional checks on all parts recovered
  - Thickness of bearing races, spacers especially
  - Length of the axle
- Cross section and metallurgical analysis of the nut and hub center at the location of the threads, to establish if the "filled in" portions of the thread on the hub are in fact the stripped threads of the nut
- Closer Inspection of the rolling elements for any damage

4.1.12 Conclusions drawn from the review of the damaged parts

Based upon the parts found and their location, the preliminary conclusion is that the bearing radial clearance increased due to a loss of preload of the thrust nut on the bearing races and internal spacers. This led to an increase over time of the bearing clearance due to wear of parts to the point where the cage of the outer bearing failed.

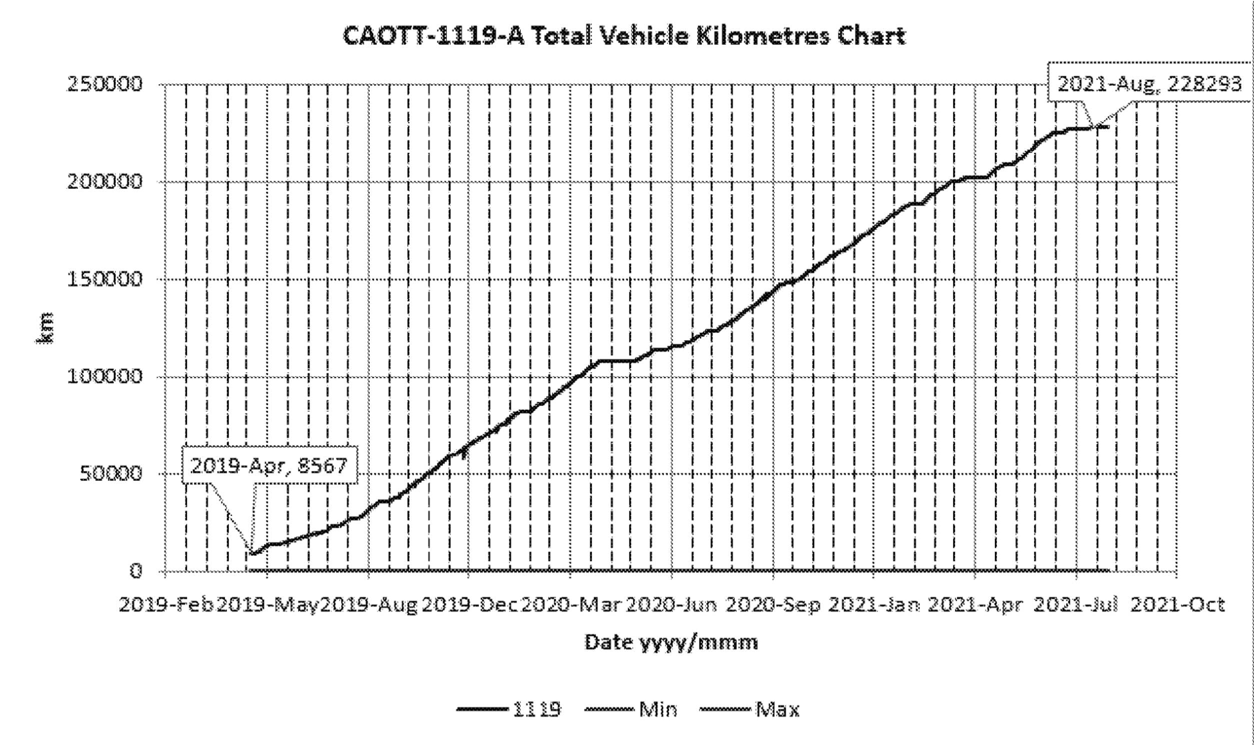
At this point there was significant metal to metal rubbing contact between the internal spacer, the hub and the outer housing, leading ultimately to a failure of the hub, releasing the wheel.

This conclusion has been used to formulate the root cause to be solved, specifically "Loss of preload on the Cartridge Bearing Assembly"

4.2 Vehicle History

4.2.1 Vehicle Mileage

LRV 1119 is currently at 228293 km. the accumulation of mileage over time is shown in the chart below.



Total LRV 1119 Milage Recorded (Apr 2019 to Aug 2021)

4.2.2 Recent train maintenance history

4.2.2.1 PREVENTATIVE MAINTENANCE HISTORY

Preventative maintenance of the LRV is done as required by the maintenance manual after the train has traveled a specific number of kilometers. . The last maintenance exam done on LRV 1119 was 25k.

4.2.2.2 25k Preventative Maintenance

The LRV was at 225374 km and the work order 60997949 was closed on Jul 3, 2021. As part of the inspection the following components relevant to the bogie were inspected during 25k:

25k Bogie Related Inspections	
System	Inspection
Bogie	Inspection of Bogie Axle beam
	Inspection of bogie frame
	Inspection of Transmission (Coupling, Motor, and Gearbox)
	Inspection of Bogie suspension (Primary and secondary)
	Anti-roll bar inspection

	VOBC Speed Sensor Inspection
	Inspection of car body to bogie connection (slewing ring and traction rod)
	Bogie Clamp Inspection
	Inspection of the track brakes
	Inspection of the sanders
	Inspection of the Wheel Flange Lubrication
	Inspection of earth/current return unit

The last 25k maintenance certificate showed that LRV 1119 bogies had some issues which were resolved through a corrective work order. The correctives performed during 25k are shown below.

Correctives Performed During 25k Preventative Maintenance		
Asset	**Issue**	**Corrective WO and Rectification**
Wheel Flange Lubricator	nozzle is not pointing towards wheel flange	61011115: Nozzle re-adjusted
Sander nozzle heating element	heating element is damaged (electrical cable is ripped off)	60949352: harnesses replaced
Track brake	adjustment required	61011112: track brake adjusted
Current Return Cable	missing heat shrink and loose in the bracket ground braid found damaged	61011113: Heat shrink added and cables retightened 61011111: New ground braids installed
Axle 2 Axle spline shaft	greasing issue where dirty grease was not coming out	61011106: WO completed
Axle 1	Grease exit screw set was stripped	61011107: WO completed
Axle 4	Grease set screw contained a broken bit	61011107: Extraction of screw was performed
Speed sensor harness bracket & clamps	Missing/broken torque marks	61011255: WO completed
Hydraulic hose pressure clamp	Missing/broken torque marks	61011255: WO completed
Ground shunt	Missing/broken torque marks	61011255: WO completed
Slewing Ring	Missing/broken torque marks	61011259: WO completed
Reaction Rod	Missing/broken torque marks	61011259: WO completed

4.2.2.3 30k Preventative Maintenance

The last 30k exam was completed on 28th May 2021 at 211,629 km. No issues regarding the bogie were reported in the work order (60913397). As part of the inspection the following components relevant to the bogie were inspected during 30k:

30k Bogie Related Inspections	
System	Inspection
Bogie	Inspection of Bogie Wheel, Shunts, and Motor

4.2.2.4 50k Preventative Maintenance

The last 50k exam was completed on Oct 22, 2019. The LRV was at 50,829 km. No bogie issues we report in the work order (60293248). As part of the inspection the following components relevant to the bogie were inspected during 50k including:

50k Bogie Related Inspections	
System	Inspection
Bogie (50k)	Inspection of Bogie Sensors

	Inspection of Wheel Flange Lubricator for any signs of leak
	Inspection of the reaction rod
	Inspection of Slewing ring
	Inspection of the anti-roll bar
	Inspection of the wiring assembly
Bogie (25k)	Inspection of Bogie Axle beam
	Inspection of bogie frame
	Inspection of Transmission (Coupling, Motor, and Gearbox)
	Inspection of Bogie suspension (Primary and secondary)
	Anti-roll bar inspection
	VOBC Speed Sensor Inspection
	Inspection of car body to bogie connection (slewing ring and traction rod)
	Bogie Clamp Inspection
	Inspection of the track brakes
	Inspection of the sanders
	Inspection of the Wheel Flange Lubrication
	Inspection of earth/current return unit
	Axle Beam Spline Shaft (Additional Greasing)

4.2.2.5 100k Preventative Maintenance

The last 100k exam was completed on April 16, 2020. The LRV was at 107,734 km. No bogie issues we report in the work order (60447939). As part of the inspection the following components relevant to the bogie were inspected during 100k including:

100k Bogie Related Inspections	
System	Inspection
Bogie (100k)	Inspection of the Bogie One shot task on the Bogie
Bogie (50k)	Inspection of Bogie Sensors
	Inspection of Wheel Flange Lubricator for any signs of leak
	Inspection of the reaction rod
	Inspection of Slewing ring
	Inspection of the anti-roll bar
	Inspection of the wiring assembly
Bogie (25k)	Inspection of Bogie Axle beam
	Inspection of bogie frame
	Inspection of Transmission (Coupling, Motor, and Gearbox)
	Inspection of Bogie suspension (Primary and secondary)
	Anti-roll bar inspection
	VOBC Speed Sensor Inspection
	Inspection of car body to bogie connection (slewing ring and traction rod)
	Bogie Clamp Inspection
	Inspection of the track brakes
	Inspection of the sanders
	Inspection of the Wheel Flange Lubrication
	Inspection of earth/current return unit
	Axle Beam Spline Shaft (Additional Greasing)

4.2.2.6 200k Preventative Maintenance

The last 200k exam was completed on April 25, 2021. The LRV was at 202,368 km. No bogie related issues were reported in the work order (60822980). As part of the inspection the following components relevant to the bogie were inspected during 200k including:

200k Bogie Related Inspections	
System	Inspection
Bogie (100k)	Inspection of the Bogie One shot task on the Bogie
Bogie (50k)	Inspection of Bogie Sensors
	Inspection of Wheel Flange Lubricator for any signs of leak
	Inspection of the reaction rod
	Inspection of Slewing ring
	Inspection of the anti-roll bar
	Inspection of the wiring assembly
	Axle Beam Spline Shaft (Additional Greasing)
Bogie (25k)	Inspection of Bogie Axle beam
	Inspection of bogie frame
	Inspection of Transmission (Coupling, Motor, and Gearbox)
	Inspection of Bogie suspension (Primary and secondary)
	Anti-roll bar inspection
	VOBC Speed Sensor Inspection
	Inspection of car body to bogie connection (slewing ring and traction rod)
	Bogie Clamp Inspection
	Inspection of the track brakes
	Inspection of the sanders
	Inspection of the Wheel Flange Lubrication
	Inspection of earth/current return unit
	Axle Beam Spline Shaft (Additional Greasing)

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4.2.3 Corrective Work Order's 6 Month History Summary

The last 6 Month corrective work order records for LRV 1119 show that a total of 112 work orders (WO). From the 112 WO, 46 WO were related to maintenance on LRV 1119's Bogies. The WOs have been organized by priority. A total of 20 priority 1 WOs were found, 18 Priority 2 WOs, 5 Priority 3 WOs, and 1 Priority 4 WO.

Bogie Corrective Priority 1 Work Orders			
Total Work Orders 20			
Order No	Event	Start Date	Finish Date
60786618	RS 1119 leveling rode in LMC2 damaged	2021-02-18	2021-02-19
60782006	RS 1119 – Flat spot turning	2021-02-16	2021-02-19
60795908	RS-1119C LHS Current return cable damage	2021-02-24	2021-02-24

60889427	RS 1119 B motor mount's hardware loose	2021-04-22	2021-04-22
61003287	Brakes #2 and 4 in minor (yellow) fault.	2021-06-28	2021-06-29
61004986	ERO reported that brakeset #2 and 4 are in yellow	2021-06-29	2021-06-30
61011111	Rs 1119 current return ground braid found damaged	2021-07-03	2021-07-03
61011106	RS-1119A axle 2 spline shaft greasing	2021-07-03	2021-07-03
61011115	Rs 1119 C WFL nozzle required adjustment	2021-07-03	2021-07-03
61011112	Rs 1119 track brake adjustment required	2021-07-03	2021-07-04
61011113	Rs 1119 current return cable missing heat shrink	2021-07-03	2021-07-04
61011255	RS-1119ABCD underframe missing torque marks	2021-07-03	2021-07-04
61011259	RS-1119BCD slew ring fasteners torque marks	2021-07-03	2021-07-04
61011300	RS-1119CD speed sensor brackets with loose fasteners	2021-07-03	2021-07-04
61038796	RS 1119 – Damaged sanding harness	2021-07-19	2021-07-30
61066322	RS1119 LMC2 LHS Track brake	2021-08-04	2021-08-05
61066916	RS 1119 – A,D wheel torque marks	2021-08-04	2021-08-05
61069717	RS 1119 All wheels need to be retorqued	2021-08-06	2021-08-06
61071091	RS 1119 – Wheel torque check hardware replaced	2021-08-07	2021-08-07
61074058	RS 1119 -Derailment	2021-08-09	2021-08-09

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Bogie Corrective Priority 2 Work Orders			
Total Work Orders 18			
Order No	Event	Start Date	Finish Date
60768032	Train overshoot at BAY STN T2 due to slippage	2021-02-08	2021-02-08
60809972	RS1119 speed sensor bracket torque check	2021-03-05	2021-03-05
60853866	Brake #2 in major fault.	2021-04-04	2021-04-05
60887609	RS 1119-D Brake Resistor Box Missing Torque Marks	2021-04-21	2021-04-21
60887993	R 1119 – C axle greasing	2021-04-22	2021-04-22
60880657	RS 1119 C greasing tank baseline required	2021-04-18	2021-04-22
60889761	RS-1119A axle 2 speed sensor bracket, loose hardware	2021-04-23	2021-04-23
60731801	RS-1119A LHS Caliper M20 bolt torque check	2021-01-13	2021-04-23
60912285	ERO reporting traction issues with max speed 35	2021-05-06	2021-05-13
60947654	Brake 2 in yellow, no IOS codes	2021-05-26	2021-05-26
60962100	RS 1119 – Brake 02 in fault	2021-06-04	2021-06-04
60961370	RS1119A axle 2 LHS wheel shunts	2021-06-04	2021-06-16
60989557	EB due to overspeed in ATO on reduction.	2021-06-21	2021-06-22
61003655	Train EB'ed due to over speed in ATO at ZC3/4 border	2021-06-29	2021-07-01
60981882	RS 1119 A&B- current return cable	2021-06-16	2021-07-03
60944057	RS1119-A-B RHS current return braid	2021-05-25	2021-07-04
61011107	RS-1119AD spline shaft stripped screw	2021-07-03	2021-07-25
61005368	RS 1119 – C SANDING HEATER cable disconnected	2021-06-30	2021-07-30

Bogie Corrective Priority 3 Work Orders			
Number of Work Orders 5			
Order No	Event	Start Date	Finish Date
60947358	Brake #2 in yellow fault	2021-05-26	2021-05-27
60961370	RS1119 A axle 2 LHS wheel shunts	2021-06-04	2021-06-16

61038796	RS 1119 – Damaged sanding harness	2021-07-19	2021-07-30
60949341	RS 1119-A Wheel shunt replacement	2021-05-27	2021-07-30
61066916	RS 1119 – A,D wheel torque marks	2021-08-04	2021-08-05

Bogie Corrective Priority 4 Work Orders			
Order No	Event	StartDate	Finish Date
60833643	RS 1119 WFL GREASING	2021-03-22	2021-04-23

4.2.4 Bogie Retrofit LRV Summary

The bogie retrofit work orders show that all 5 of the LRV 1119's Bogies were retro fitted on May 27, 2020. Also, the wheel centers were replaced for all bogies on July 16, 2021.

Order	Event	Date Started	Date Closed
70957520	INS CR9938&CR3564 Retrofit Brake caliper	2018-12-04	2018-10-24
70974264	2003 : BOGIES/ WABTEC	2020-02-05	2018-11-06
71681210	BM1 RETROFIT	2020-01-26	2020-05-27
71681214	BM2 RETROFIT	2020-02-10	2020-05-27
71681213	BM3 RETROFIT	2020-02-10	2020-05-27
71681212	BP1 RETROFIT	2020-01-26	2020-05-27
71681211	BP2 RETROFIT	2020-01-26	2020-05-27
71681216	Bogie retrofit generic activities	2020-02-10	2020-01-20
71814686	RETROFIT SANDING PIPE SHIELD	2020-04-22	2020-04-22
72809712	BM1 WHEEL CENTER REPLACEMENT	2021-07-27	2021-07-16
72809713	BM2 WHEEL CENTER REPLACEMENT	2021-07-28	2021-07-16
72809714	BM3 WHEEL CENTER REPLACEMENT	2021-07-28	2021-07-16
72809715	BP1 WHEEL CENTER REPLACEMENT	2021-07-28	2021-07-16
72809716	BP2 WHEEL CENTER REPLACEMENT	2021-07-22	2021-07-16
72810154	Retrofit support equipment BM2	2021-07-28	2021-07-16
72810155	Retrofit support equipment BP2	2021-07-22	2021-07-16
72809717	WHEEL CENTER REPLACEMENT TRAIN LIFTING	2021-07-19	2021-07-16
72809719	NRT for Bogie Program		2021-07-16

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4.2.5 Last Wheel Reprofile Results

Wheel Truing was done because of a Bogie change caused by the axle spline greasing in the last 25k. The LRV's wheel reprofiling (61056091) was completed on Aug 3rd, 2021 at 227,558 km. The last wheel reprofiling was done on 29 July 2021.

While reviewing the lathe's wheel data base for LRV 1119, in hindsight, it was found that axle 2 back to back distance was above the max tolerance of 1381mm, and axial runout of axle 7 was slightly above the max. tolerance.

Wheel Lathe Data for LRV 1119 – July 29th

Axle	back to back [mm]	Wheel Diameter		Flange Height		Flange Thickness		Axial Runout	
		Left	Right	Left	Right	Left	Right	Left [mm]	Right [mm]
1	1379.01	639.47	639.73	26.06	26	23.82	23.89	0.19	0.25
2	[redacted]	639.63	639.79	25.98	25.97	23.97	23.82	0.15	0.49
3	1378.89	629.96	629.58	25.98	25.99	23.7	23.84	0.15	0.46
4	1380.8	626.88	627.27	25.96	26.01	23.84	23.92	0.31	0.58
5	1379.14	613.51	613.19	25.99	26.02	23.73	24.04	0.62	0.72
6	1380.94	616.16	616.07	26.01	25.94	23.79	23.96	0.08	0.56
7	1379.09	625.13	625.39	25.98	25.97	23.85	23.84	0.38	[redacted]

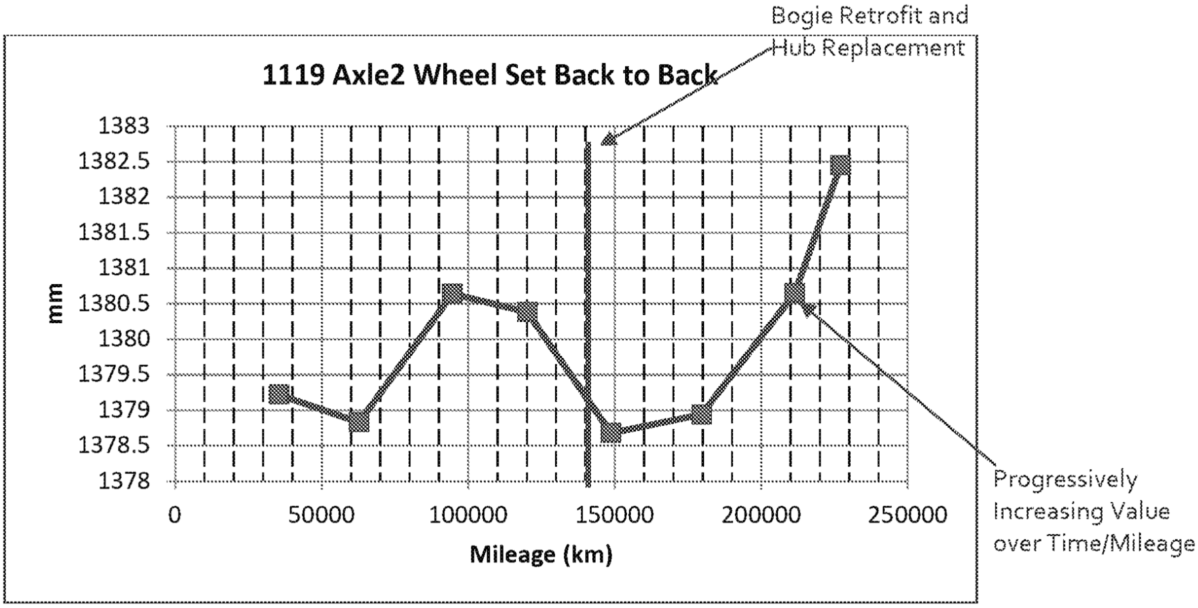
8	1380.76	621.55	622.35	26.01	25.98	23.7	23.94	0.65	0.46
8	1380.84	621.53	622.45	26.04	25.99	23.76	23.66	0.63	0.26
11	1379.55	632.19	631.88	25.96	26.04	23.99	24.11	0.72	0.25
12	1380.74	630.36	630.8	26.02	25.94	23.86	24.22	0.22	0.67

The table of tolerance is shown below for each of the parameters monitored during the wheel turning process

Wheel Specifications (mm)		Reprofile ref
Back to back (Ei) bogie without load		1378 ±1
Back to back (Ei) bogie under load		$1378\ ^{-1}/_{+3}$
Flange gauge (Ea = Ei + Sd_Left + Sd_Right)		1426.4 ±1.5
Axial run out (V) *		< 0.8
Radial run out (FR) *		< 0.5
Diameter (D)		> 573
Diameter difference between 2 wheels **of same wheelset**	Motor Bogie	< 0.5
	Trailer Bogie	< 1
Diameter difference between wheels on the same bogie	Motor Bogie	< 6
	Trailer Bogie	< 12
Diameter difference between wheels on different bogies	Motor Bogie	< 39
	Trailer Bogie	< 39
Flange height (Sh)		26 ± 0.25
Flange thickness (Sd)		24.2 -0,5/+0,25
Difference between flange thickness on same wheelset		< 0.4
qR cross measure		> 4

Wheel Profile Tolerance limits

Upon review of the wheel lathe data, and specifically the very high back to back values for axle 2, the past records for that axle were reviewed. The chart below shows the summary of that review



4.2.6 Conclusions from review of the vehicle history

The apparent evolution over time of the back to back distance of the failed axle indicated that there was an issue with the clearance of the cartridge bearing assembly increasing over time. This is consistent with the physical findings from the failed hub.

There are no other findings in the vehicle history that appear to be relevant to the failure and / or derailment.

5 Root cause analysis

Identification of the root cause to investigate, followed the 5 Why process.

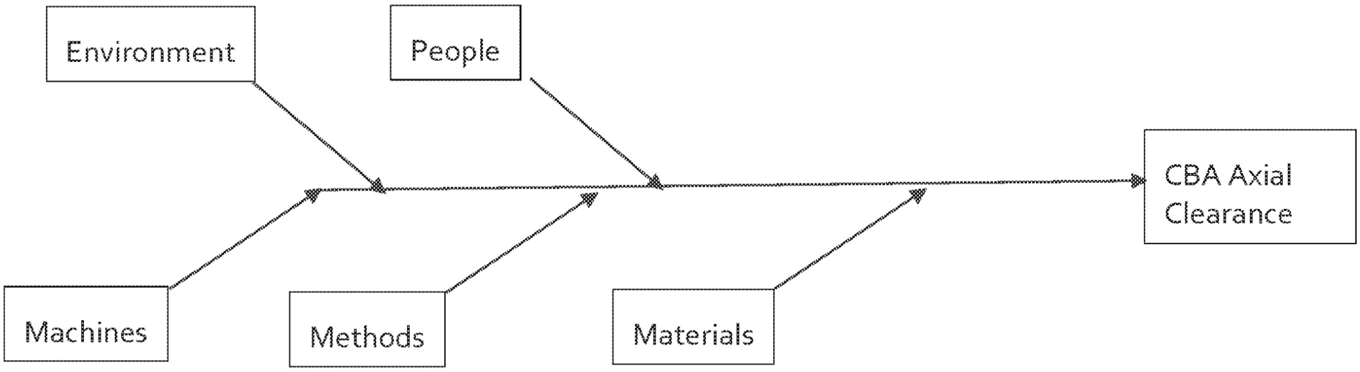
LRV 1119 derailed

- ➔ Why
  - ➔ The wheel separated
    - ➔ Why
      - ➔ The Hub Separated
        - ➔ Why
          - ➔ The Outer Bearing came apart
            - ➔ Why
              - ➔ The internal assembly lost the preload

This was evident very quickly from the inspection of the parts and inspection of other hubs that demonstrated excessive axial clearance of the CBA

Having established the issue to be investigated, an Ishikawa diagram was developed to identify all the potential root causes, and lead the investigation through the resulting data.

5.1 Ishikawa Diagram



If we consider the 5 possible sources of the root cause we have the following specific points to consider. These are listed in order to keep the diagram simple at the top level

People

- Error in crimping the nut to the hub
- Incorrect calculation / setting of bearing clearance and hub preload
- Poor installation of the shaft seal seat including omission of Loctite under the seat
- Poor installation of the thrust washer
- Poor installation and pressing of the inner bearing
- No grease in the bearings

Environment

- Environment changed outside of original analysis, or incorrect specification of environment.
  - This can be split into two potential areas, the track, and
- Ineffective regreasing of the bearing

Machines

- Malfunction or incorrect application of the electrical torque wrench

Methods

- The tightening torque is too low

Materials

- Impact of design evolution (V to V4)
- Material hardness non compliances
- Dimensional part non compliances
- Non conforming or defective bearings

5.2 Specific investigations

In order to address the possible root causes, several specific investigations have been started to supply information that will be used to either include or exclude root causes.

These investigations include

- teardown and analysis of the hubs
  - One hub from LRV 1118 That was found to have excessive clearence was disassembled in Ottawa, all the parts and grease samples have been sent to labs for analysis
  - The remaining hubs have been returned to Texelis for similar analysis.
- A complete process review of the assembly operation at Texelis,
- A review of the materials used in the CBA
- A review of the track history, including assessment of the vibration environment as a result of the track condition
- A review of potential wheel flats as a source of excess load
- A review of the design input file load cases, against Texelis documentation
- A finite element modulization of the hub to assess in detail all the components including the rolling elements.
  - To support this effort, a test regime is planned for the Ottawa site, with instrumented hubs to validate the calculations and fine tune the model

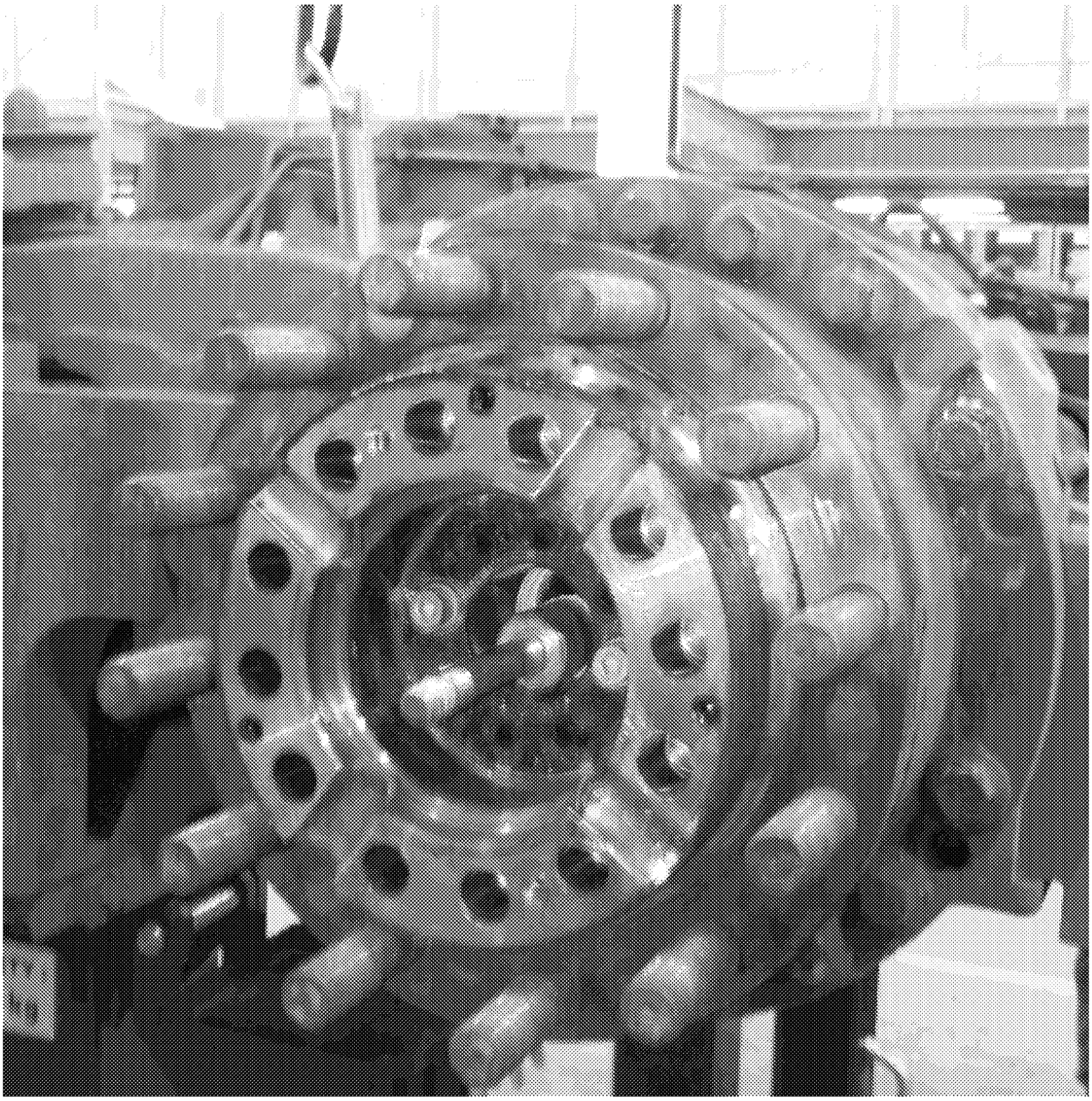
5.2.1 Hub Teardown results

5.2.1.1 Tear down summary of TS 18 axle

The bogie was removed from the train and set on bogie stands, and prepared for Texalis representatives to remove the bearing and hub assembly.

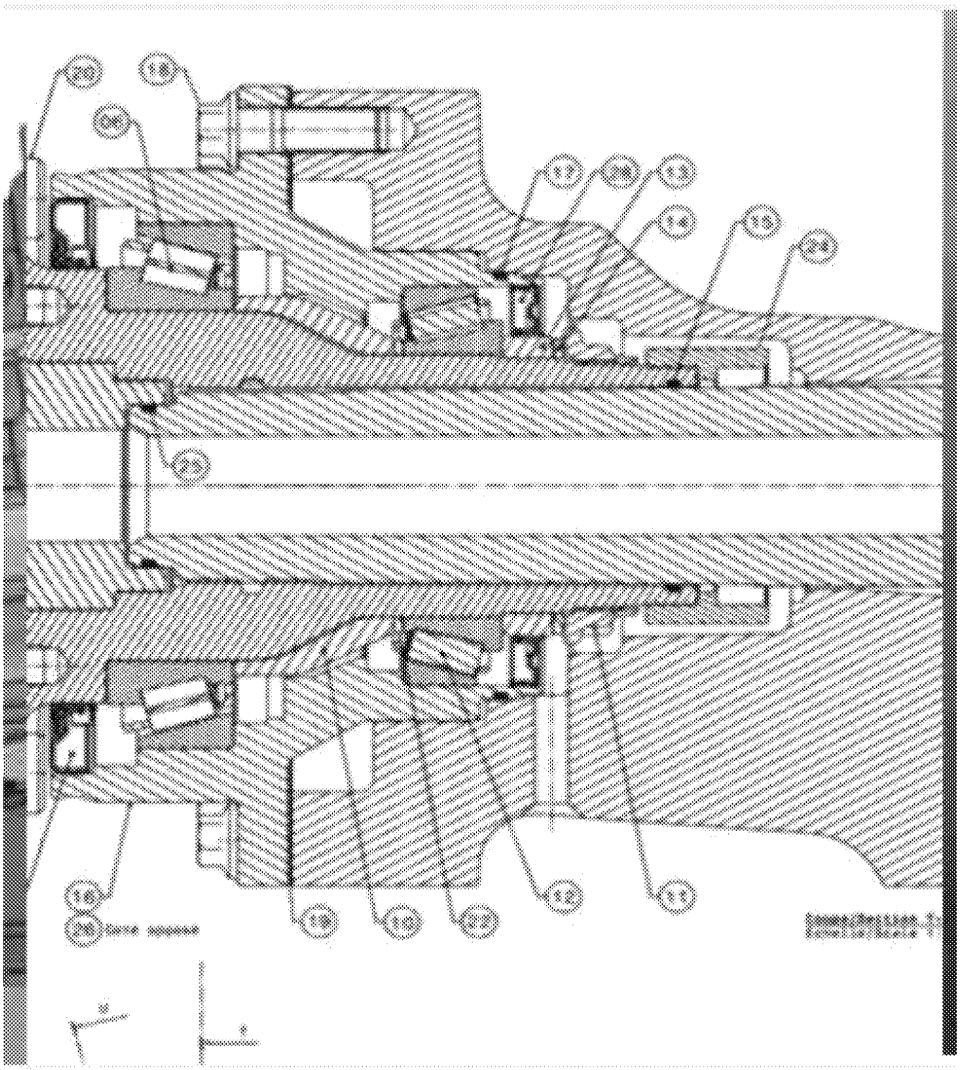
Prior to the removal of the hub, the axle backlash of the axle splines was checked and found to be 20mm.

The defective hub, shown in figure 1 below is number 191843R



View of hub installed on the axle beam, ready for disassembly

This is achieved by removing the bolts (item 18 in the Figure below)



Cross section of the hub assembly

With the hub removed, there were some marks on the exterior of the bearing capsule / hub assembly that might indicate the assembly was hot at some time in the past, this can be seen in the figure below. It has been reported that there is some heating applied to the assembly to insert the bearing race, therefore this may simply be an artifact of the assembly process.

Discoloration of the bearing cartridge

The cartridge was set on a bench, and the bearing retention nut was checked for tightness and for the depth of the mechanical "Swaging" of the nut into the shaft slots. One of the swage marks is visible in the figure below.

View of the speed sensor target wheel, and bearing retention nut

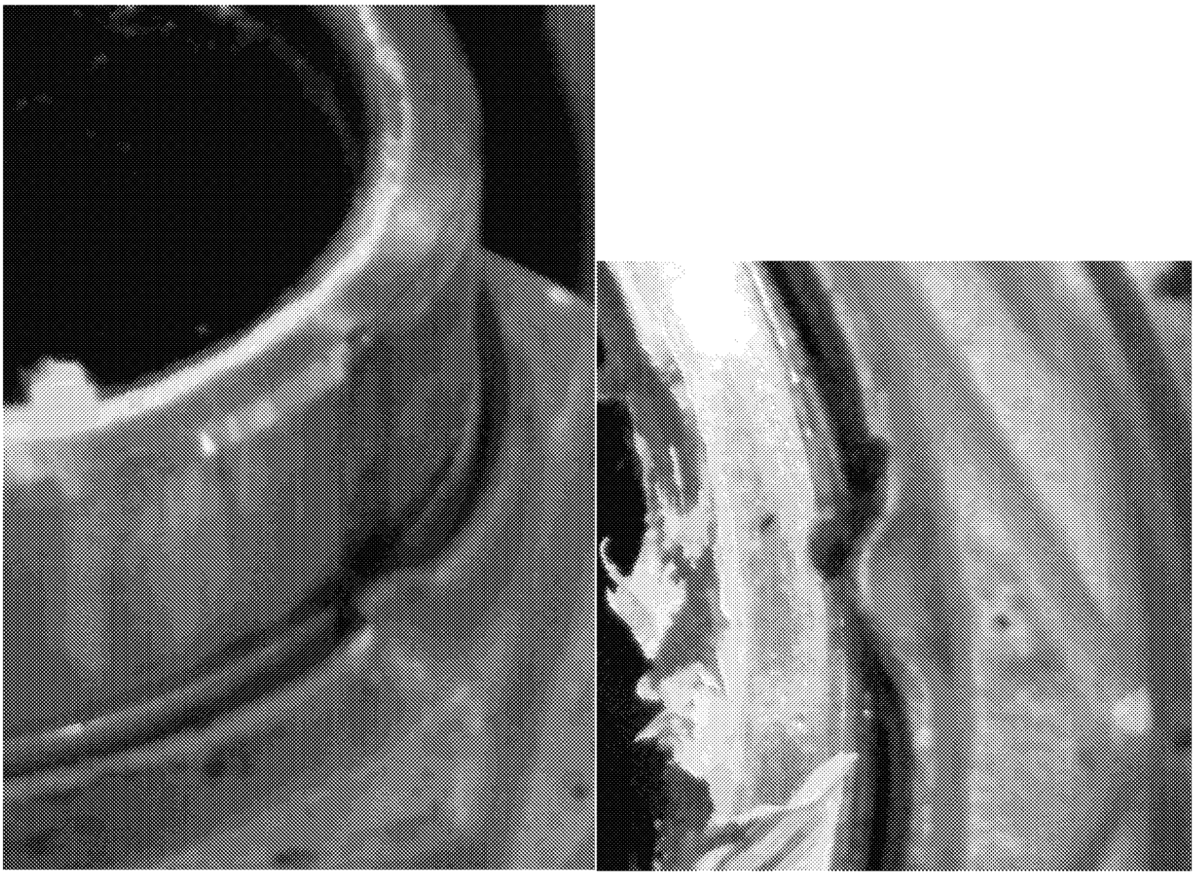
The nut was found to be completely loose, and could be turned back and forth within the width of the slot it should extend into.

In addition, the nut was completely free to slide back and forth radially, the fit of the nut onto the threaded shaft is extremely loose. The intended thread fit is not known.

With the assembly sitting vertically as shown in the preceding figure, the clearance between the nut, and the thrust spacer (item 14 of the cross sectional diagram) was checked with feeler gauges. Several feeler gauges of between 102um and 203 um all easily fit into the space, 305um was tested but could not be inserted, but 279um gauge was able to be inserted into the space between the washer and the nut. This measurement is in good agreement with the pry bar measurement on the train, validating the pry measurement on the train.

Following discussion and agreement with Texelis, and their local representatives, we proceeded to disassemble the assembly, the first part removed was the target wheel for the axle speed sensor.

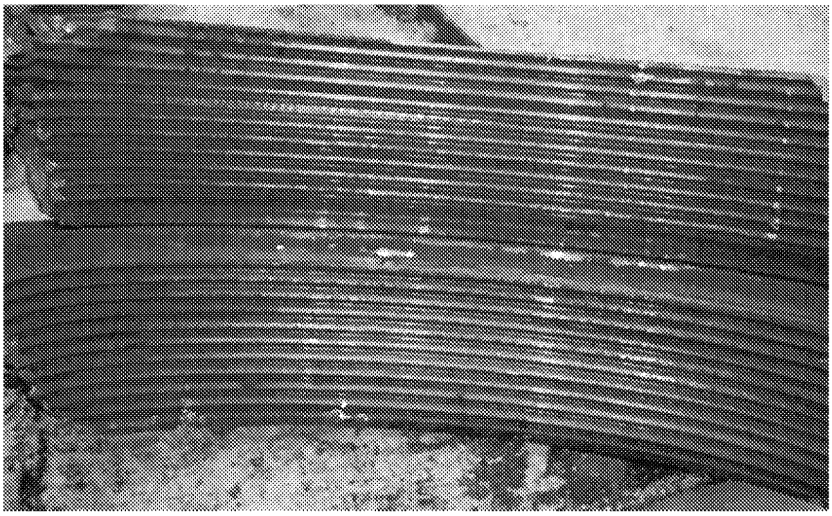
With the speed sensor target removed, the depth of the mechanical swaging could be better evaluated, and can be seen in the figure below



Swaging marks on the bearing retention nut

Removal of the swaging nut was difficult and required cutting in two with an abrasive disk.

The threads are shown below. There is a considerable amount of fretting corrosion present. Note that the lighting at the time led to a slightly exaggerated or enhanced depiction of the corrosion

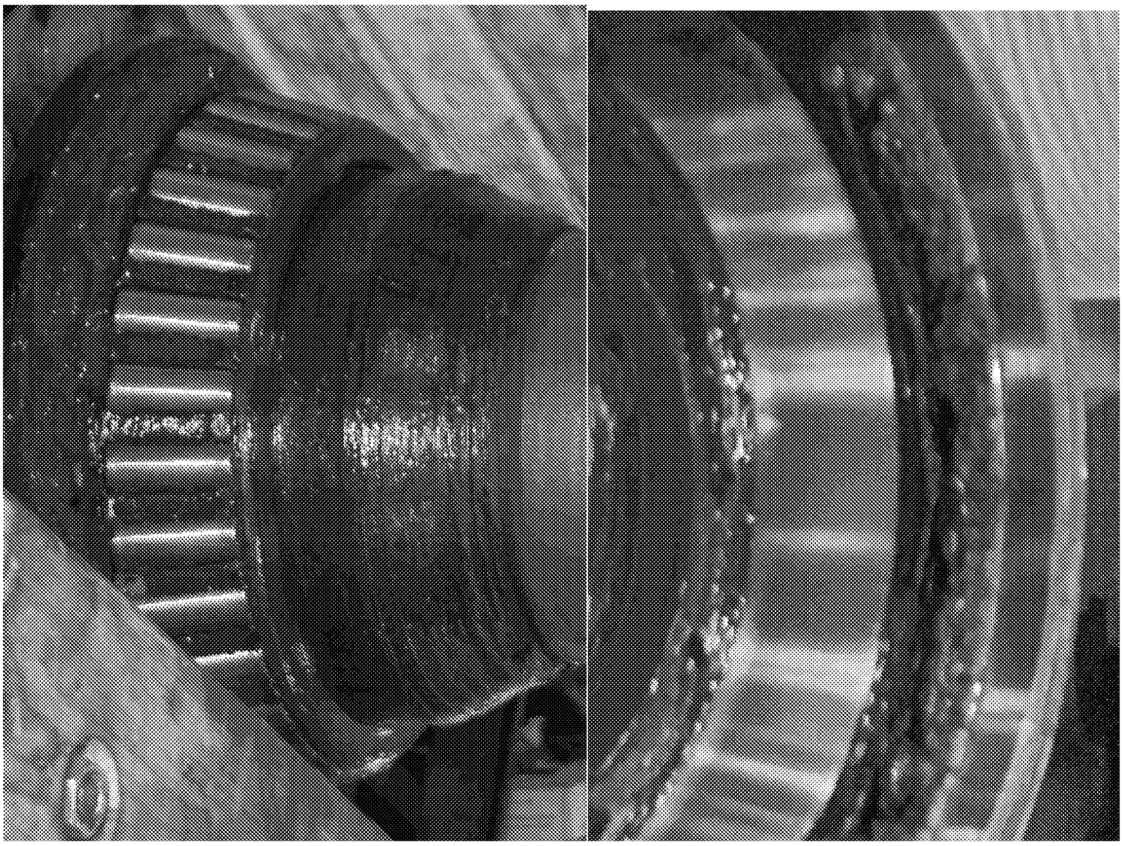


Bearing retention nut thread condition

The shaft threads on the hub are in a similar condition, as is the shaft under the shaft seal seat and the inner race of the bearing.as shown below; again the lighting at the time has exaggerated the level of the corrosion

Hub condition below the bearing shaft seal and nut

To view the bearings the hub had to be pressed out of the cartridge casing, The bearing condition was reviewed starting with the large outer bearing. This is shown in the following figure. Overall the condition is quite good, there is no serious discoloration of the rollers and the grease is quite clean near the bearing.



Outer bearing race and rollers

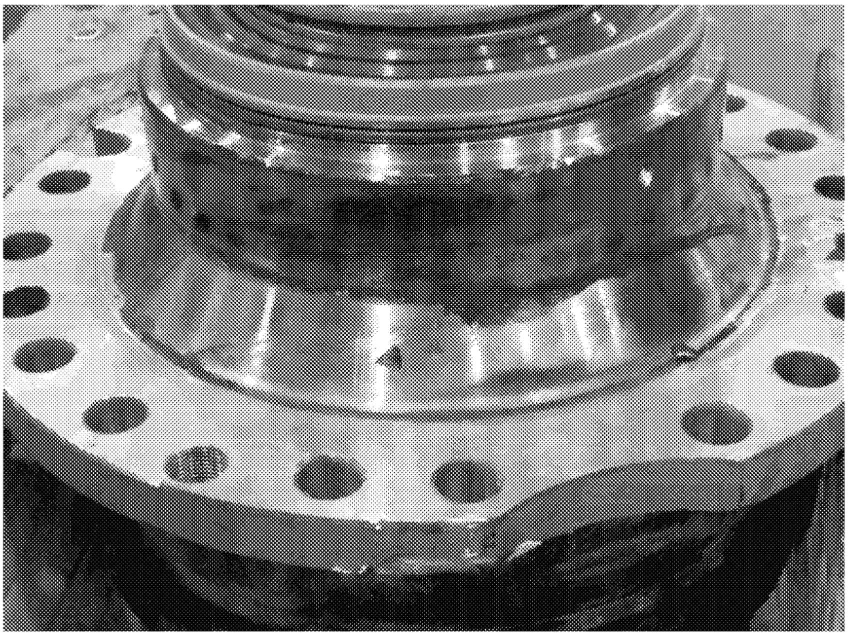
Both the rollers and race are in good condition and there is no evidence of fatigue spalls present.

The small inner bearing condition was not as good. There is some possible discoloration present on the rollers and the condition of the grease is the complete opposite of the larger bearing, as can be seen in the figure below

Inner (small bearing)

The opposite side bearing cartridge was removed and inspected, overall while there was some discoloration it was less than on the side with large axial clearance in the bearing, The bearing locking nut was checked and found to be tight with no play.

The overall appearance is shown in below;



Opposite side hub assembly removed

As an overall comment, the condition of the rollers and race where the appearance was shinny and not "frosted" suggests that there is no damage from electrical discharge.

Grease samples were taken from the following locations

- Small bearing from the shaft seal
- Small bearing cage smaller diameter side
- Small bearing cage larger diameter side
- Large bearing cage between the rollers
- Large bearing cavity at the top where there was evidence of splatter of grease thrown from the bearing into the void of the cavity (this action is normal)

follow on investigations on these parts will include

- analysis of the "rust or fretting corrosion" to confirm the assumptions
- surface analysis and cross section with etching of the bearings to confirm;
  - no electric discharge took place
  - there is evidence of overheating
- surface contour of the bearing s and rollers for wear.
- Surface inspection of the contact surfaces, to assess wear, sliding and compression of the joint fit up.
- Measurement of the thickness of all parts, to compare against the design.
- Grease analysis and metallic content.

5.2.1.1.1 Grease analysis results

The analysis of the grease in the bearing cavity has been done to determine whether there are any significant wear indicators from the various metal parts, as well as determining if there was any external contamination, incorrect grease installed, etc.

Two principle methods were used, metallic content, and infra red spectroscophy.

5.2.1.1.1.1 Metallic content

To illustrate, the following tables indicate the typical types of metals found in bearing steels, and the typical metals that can be found in greases as part of the additives, and also external contamination (dirt)

Typical bearing steels content					
ELEMENT	% WEIGHT				
	SAE 52100 (USA)	AISI 440C (USA)	100CR6 Germany	SUJ2 Japan	GCR15 China
Carbon	0.95 - 1.1%	0.95 - 1.2%	.95-1.1	.95-1.1	.95-1.05
Chromium	1.3 - 1.6%	16 - 18%	1.35-1.65	1.3-1.6	1.4-1.65
Silicon	0.15 - 0.35%	1% max	.15-.35	.15-.35	.15-.35
Manganese	0.5% max	1% max	.25-.45	.5 max	.25-.45

Molybdenum	0.08% max	0.75% max	.1 max	.08 max	.1 max
Phosphorous	0.012% max	0.04% max	.03 max	.025 max	.027 max
Nickel	0.25% max	0.25% max		.25 max	.23 max
Sulphur	0.25% max	0.30% max	0.2 max	0.25 max	0.2 max

Other Elements typically found in grease			
EP oil additives	Typical grease contents	Klüberpaste 46 MR 401 (Spline)	Dirt and external contamination
sulphur	lithium	lithium	Silicon
phosphorus	calcium	zinc	Calcium
molybdenum	sodium	sodium	Iron
	aluminum	antimony	Aluminum
	titanium	titanium	Manganese

The following table shows the actual findings from the grease samples collected from the CBA removed from LRV1118

	Outer Bearing Cage	Inner Bearing Cage Bottom	Inner Bearing Cage Top	inner Seal	Outer Bearing Grease Pack	New Grease for the hub	New Spline Shaft
Metals Analysis by ICP, Aqueous							
Element	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Aluminum (Al)	5.3	165	83.9	12.2	4.4	9.8	407.8
Barium (Ba)	< 1.0	5.3	5.6	4.7	2.2	< 1.0	< 1.0
Bismuth (Bi)	1.1	14.8	12.7	2	1.1	1.2	6.7
Calcium (Ca)	25.6	134	84.1	34.9	20.9	23.6	17070
Cadmium (Cd)	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	1.1
Chromium (Cr)	6	705	862.6	354.2	32.1	< 1.0	1.5
Copper (Cu)	< 1.0	782.2	366.4	77.7	< 1.0	< 1.0	12.8
Iron (Fe)	427.3	58600	68180	7097	879	101.5	37.4
Potassium (K)	9.8	56.9	42	9.8	8	39.7	91.4

Lithium (Li)	2828	582.5	1393	1788	2860	1663	1078
Magnesium (Mg)	3.6	< 1.0	< 1.0	< 1.0	< 1.0	4.3	90.2
Manganese (Mn)	3.4	417.4	460.8	196.9	14.2	< 1.0	< 1.0
Molybdenum (Mo)	2.7	688.6	372.1	49.1	4.2	6.2	351.3
Sodium (Na)	40.6	62.6	56.8	43.4	10.7	64.9	3294
Nickel (Ni)	3.2	680	626.1	82.1	4.8	3.1	< 1.0
Phosphorus (P)	517.7	228.3	474.7	1056	1792	853.8	25440
Lead (Ph)	1	43.7	21.4	2.8	1.4	1.7	< 1.0
Sulfur (S)	3164	3478	4526	4497	7760	3892	< 1.0
Antimony (Sb)	5.5	< 1.0	< 1.0	4.2	9	15.2	7.2
Selenium (Se)	9.1	< 1.0	< 1.0	9.2	13.6	29.3	< 1.0
Silica (Si)	30.6	1523	1009	138.2	31.4	99.6	221
Tin (Sn)	7	42.85	29.6	14.2	10.2	18.8	< 1.0
Tellurium (Te)	< 1.0	93.01	57.9	< 1.0	< 1.0	< 1.0	< 1.0
Titanium (Ti)	< 1.0	20.42	11.7	1.5	< 1.0	< 1.0	200.4
Vanadium (V)	< 1.0	81.25	49.1	5.2	< 1.0	< 1.0	6.8
Zinc (Zn)	780.8	392.1	978.3	403	1213	787.1	88570

Within the values reported, any entry showing < any value, means that the element in question was not detected and the value to the right is the minimum detection threshold based on the sample size.

Within the elements found and the concentration, there are several that require further investigation.

The presence of tellurium (Te) is of specific interest because it is not normally found in bearings, and because it is used in steels to make them easier to machine. As it was found only at the inner bearing, it suggests one specific part is subject to wear. This will require analysis of the metallic parts to determine the part in question.

In addition there is a high amount of copper also found near the inner bearing, which cannot be explained in the concentrations found.

The level of iron found is consistent with the level of corrosion observed.

From the other samples it is difficult to determine whether some of the elemerns are wear metals from the parts in the CBA or from the migration of the grease between the spline and the internal parts of the CBA.

5.2.1.1.1.2 Infra red Spectroscopy

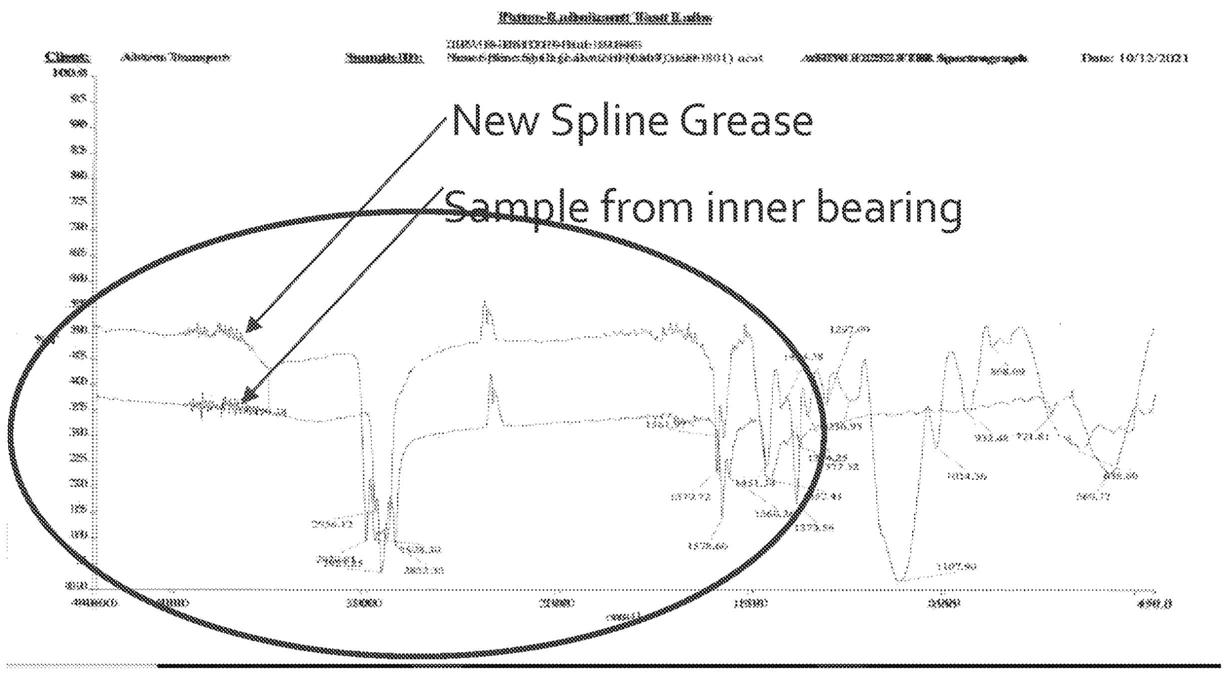
Infra red Spectroscopy determines the resonant frequencies within the atomic bonds of the different grease constituents.

This can be used primarily to evaluate from the spectrum one grease and or oil from another. This is similar to a human fingerprint.

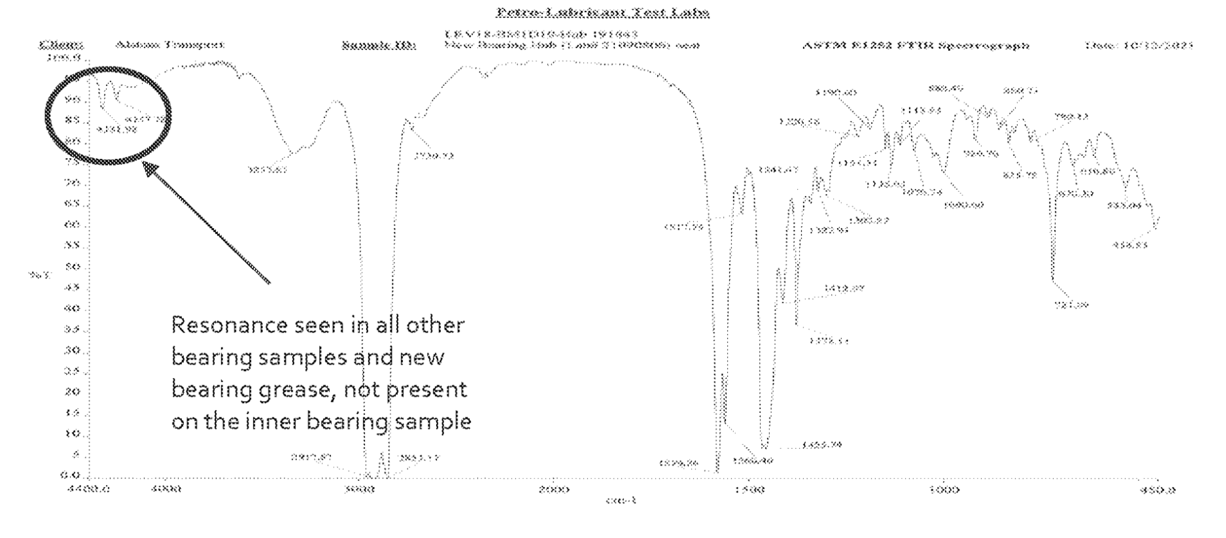
From the grease samples taken, there were two findings of note.

One sample taken from the inner bearing, exhibited a similar spectrium over the range of wavelengths between 1000 and 4000 nm to that of the spline grease.

This can be seen in the charts below that were overlayed in a photo editor for direct comparison



In addition, this sample is missing a resonance observed in all other samples taken from the internal area of the CBA, as can be seen below.



It is difficult to imagine a means of the spline grease entering the bearing area of the CBA.

5.2.1.1.2 Lab analysis of the metallic parts

pending

5.2.1.1.3 Conclusions from the Teardown analysis

There is sufficient grease overall to exclude the failure to add grease during the assembly process, however the possible mixing of the bearing and spline grease at the inner bearing needs further investigation.

5.2.1.2 Teardown of returned hubs to Texelis

5.2.1.2.1 Soft material in the stack-up

Material

- **Design**
- **Quality**
  - Materials analysis to be done on all metallic parts of disassembled hub.

Heat Treatment

- **Design**
- **Quality**
  - Materials analysis to be done on all metallic parts of disassembled hub.

5.2.1.2.2 Quality of the nut

Materials analysis to be done on all metallic parts of disassembled hub.

5.2.1.2.3 Quality of the hub

Materials analysis to be done on all metallic parts of disassembled hub.

5.2.2 Vendor Process Analysis

Process Audit was held at Texelis (axle supplier) on Sept, 09th, 2021 with ALSTOM presence. The following points were demonstrated:

· High quality standard of the global process

· Computer Assisted Production Management system

· Electronic Torque wrench with automatic record & release

· Skilled operator & Global 5S of the production area

The following assembly steps were also implemented to avoid non-conformance

· Torque tightening (electronic torque wrench)

· Bearing clearance setting (motorized push/pull & rotation)

· Greasing (volu-counter)

However, there was one point of concern that was raised related to the cold fit of the flange within the hub. Initial analysis showed that there is an influence. After deeper analysis, this influence was demonstrated to be minor and does not explain the phenomenon that caused the derailment.

The detail of the process review follows

5.2.2.1 Torque application

The audit of the hub assembly process was performed by Alstom personnel in September 2021 in Texelis facility in Limoges, France. High quality standard of the global assembly process was demonstrated.

The hub retention nut (Fig.3, pos.11) tightening process is automatic with the control of torque value and the angle. GO/NOGO visualization of the step completion and conformity on the screen (GREEN/RED). Information is recorded to Texelis production management system. Nut tightening value is 2000 Nm with the precision of +/- 10%.

Statistical analysis of retention nut tightening data on Ixege-Iponam-Ipomos hubs produced in the period from June 2019 to August 2021 showed that the hubs with axial clearance do not appear as abnormal compared to the rest of the population. Refer to Figure X

The measurement of residual torque values of the retention nut during the expertise of the hubs with the axial clearance revealed that there is no loss of initial torque value.

Taking into account the above-mentioned findings the torque application was excluded from the possible root-causes of the axial clearance apparition.

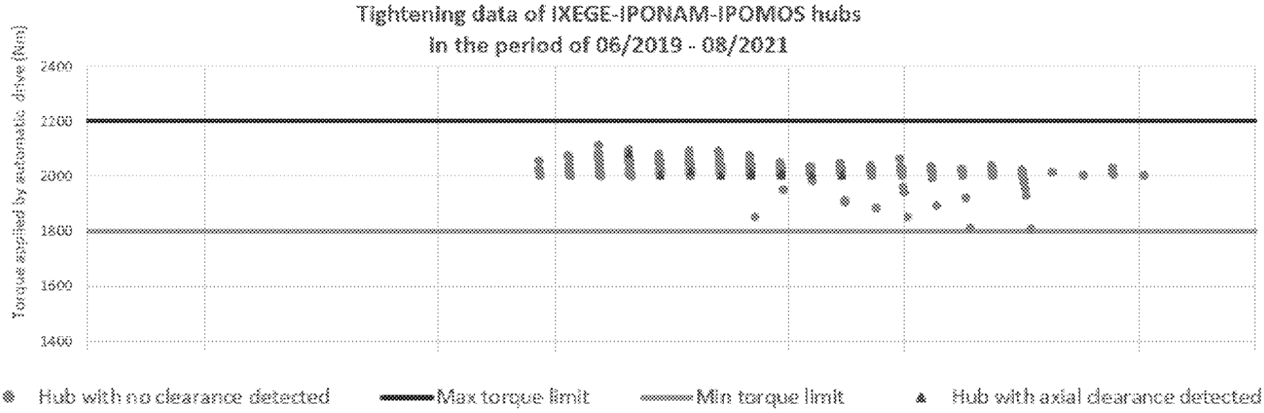


Figure 1. Historical data of retention nut tightening values during fabrication in Texelis 06/2019-08/2021

5.2.2.2 Loss of tension after torqueing

5.2.2.2.1 Impact of the crimping process

Loss of torque after shock

According to the hub assembly process after torque tightening of the retention nut to 2000 Nm, the nut is crimped against the grooves in the hub in 2 diametrically opposed places to prevent nut unscrewing – see Figure 7.

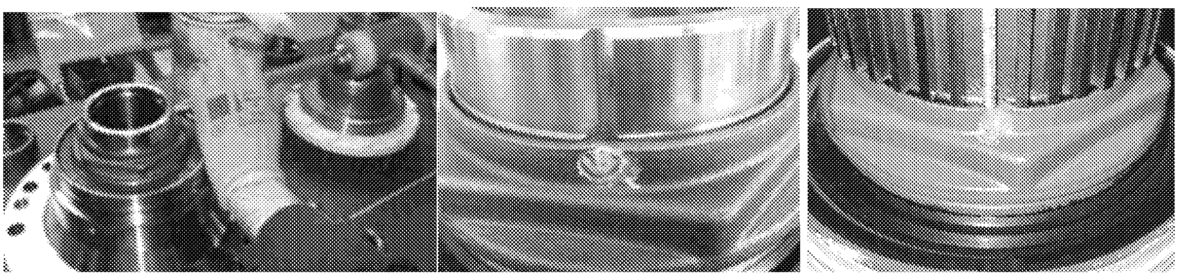


Figure 2. Crimping of the retention nut

A series of tests were realized to determine the influence of nut crimping on the nut torque value. The first series of test consisted in a) tightening a nut to 2000 Nm without crimping and measuring the residual torque immediately after and b) tightening a nut to 2000 Nm without crimping and measuring the residual torque 1h after. The second series of test consisted in a) tightening a nut to 2000 Nm, manual crimping and measuring the residual torque immediately after and b) tightening a nut to 2000 Nm, manual crimping and measuring the residual torque 1h after. The resulting torque-angle curves are given on Figures XX.

We can conclude that crimping of the nut has no influence on the nut torque value.

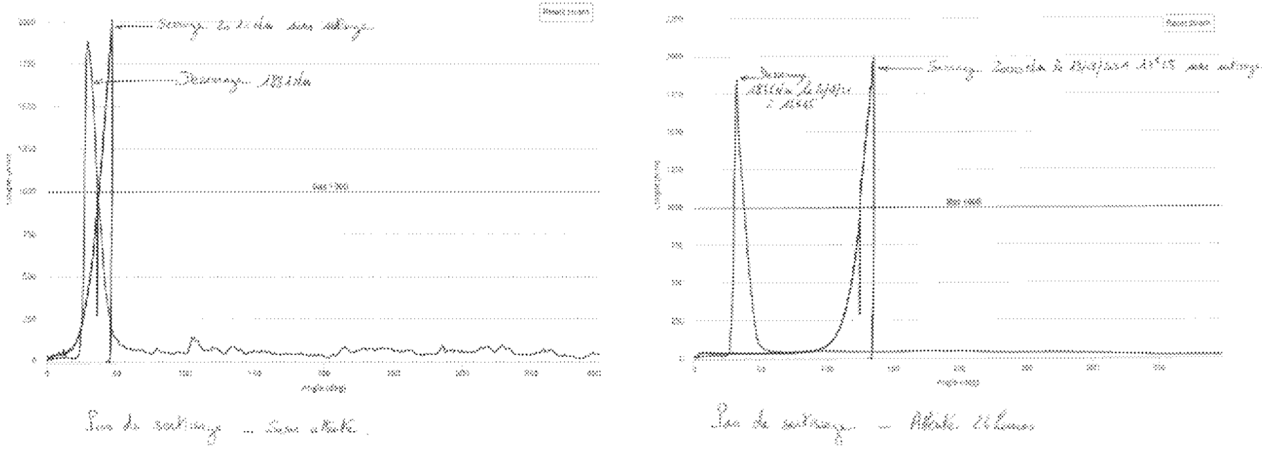


Figure 3. Torque measurement - Nut without crimping

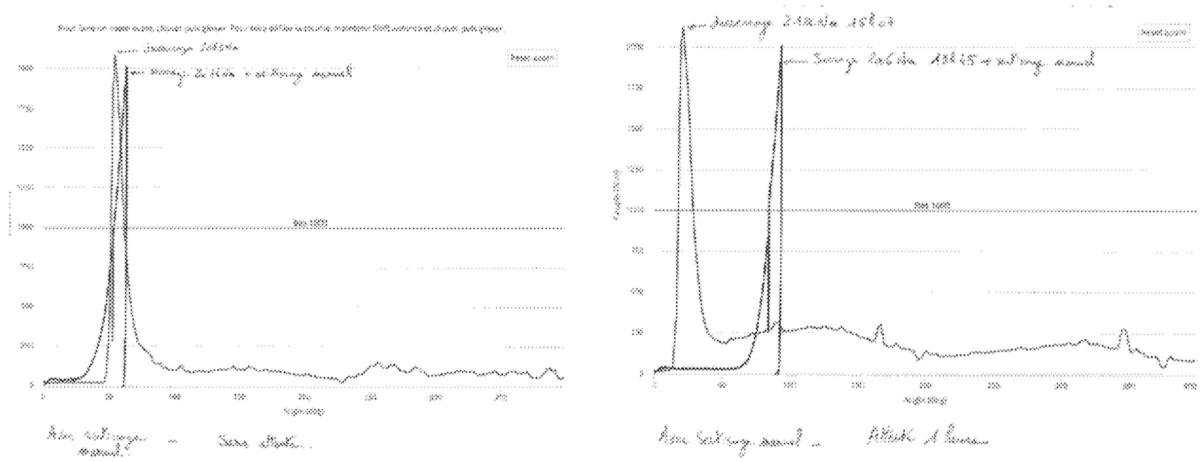
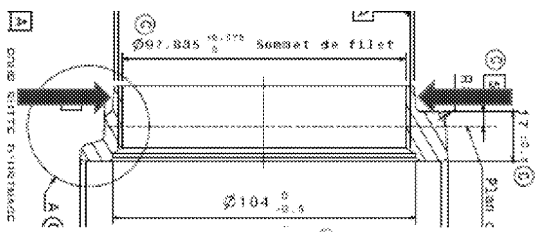


Figure 4. Torque measurements - Nut with crimping

Ovalization of the nut

5.2.2.2.2 Deformation measurement:

- before crimping ovalization of 0.02
- after crimping ovalization of 0.4



5.2.2.3 Residual clearance within the stack

5.2.2.3.1 Gluing of the sealing ring

According to hub assembly process the under-seal ring (Fig.3 pos. 13) is manually installed on the hub with the use of Loctite 518 on its inner diameter as shown on Figure X. The next assembly step after under-seal ring installation is the torque tightening of the retention nut.

According to Loctite 581 technical data sheet the cure time within first hour following the application is below 20% of full shear strength when used on steel at 22°C (Figure X). As retention nut tightening is performed shortly after the under-seal ring installation, we can conclude that Loctite 518 does not influence correct axial clearance set up.

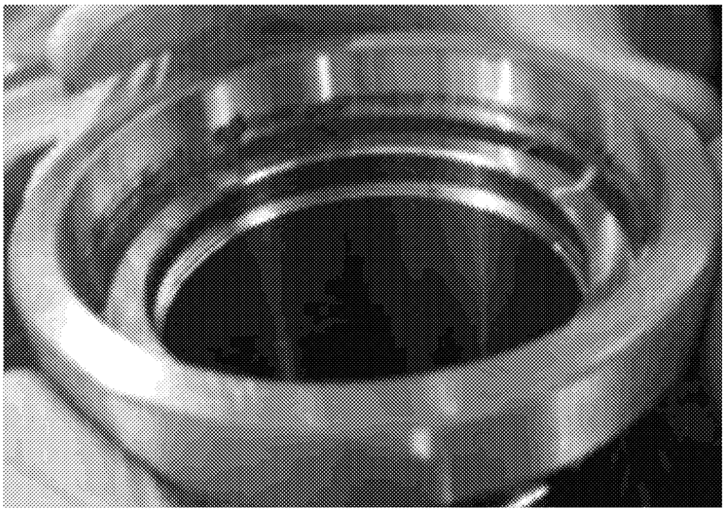


Figure 5. Under-seal ring installation on the hub

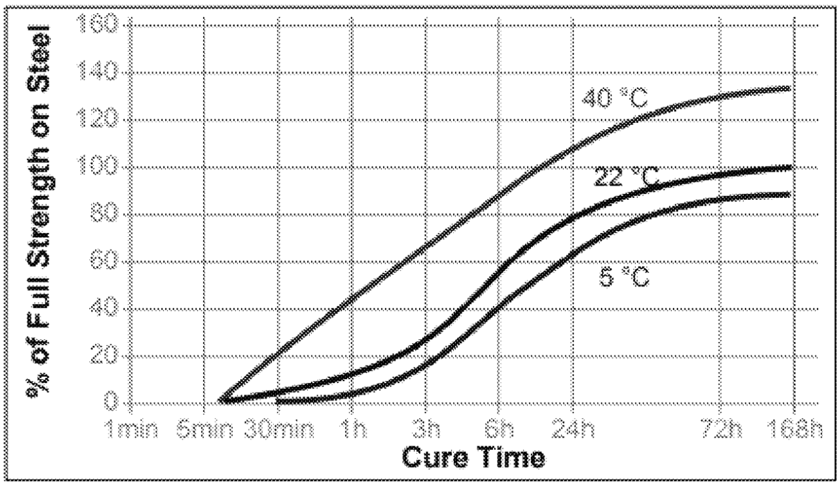


Figure 6. Loctite 518 cure time curve at different temperatures (Source: Loctite 518 technical data sheet)

5.2.2.3.2 Wrong press load force

According to the calculations the press-fit force of the inner ring is between 1.2T and 4.1T for the small bearing and between 2T and 6.8T for the inner ring of the large bearing. During the fabrication of hubs Texelis uses 2 hub assembly stations each equipped with a press. Nominal capacity of the presses is 20T and 12T. So, the presses nominal capacity is sufficient for the requested press-fit force of inner rings installation. The calibration reports of both presses are given below in the Tables X and Y.
The control of correct installation of the inner ring is realized with a shim of thickness 0,04mm that should not pass between the inner ring face and the hub face as shown on Figure X.

Table 1. Calibration report of 20T press (25/08/2020)

Justesse

Pt	Consigne (kN)	Valeurs Etalons (T)	Valeurs Etalons Converties (kN)	Valeurs mesurées (kN)	Écart (kN)
1	20	2,18	21,4	21,0	-0,4
2	70	6,89	67,6	68,0	0,4
3	80	8,12	79,7	80,0	0,3
4	100	8,83	86,6	86,0	-0,6
5	110	10,13	99,4	100,0	0,6
6	120	10,96	107,5	108,0	0,5
7	160	16,49	161,8	162,0	0,2

Erreur maxi : -0,60 kN

Table 2. Calibration report of 12T press (10/06/2021)

Répétabilité

Pt	Consigne (T)	Valeur instrument (kN)	Valeurs étalons (T)	Valeur étalon (kN)	Écart (kN)
1	12	82	11,76	115,4	33,4
			11,74	115,2	33,2
			11,78	115,6	33,6
			11,78	115,6	33,6
			11,82	116,0	34,0
			11,85	116,2	34,2
			11,81	115,9	33,9
			12,18	119,5	37,5
			11,78	115,6	33,6
			11,93	117,0	35,0
			Écart type (kN) : 1,3		

Figure 7. Control of correct installation of the bearing inner ring using a shim of 0,04mm

5.2.2.4 Grease quantity

During the assembly process in Texelis factory the bearings grease quantity is controlled using a volume meter, Figure X.

The inspection of LRV18 axle 1 hub with axial clearance showed the presence of adequate quantity of grease (refer to the LRV 1118 teardown observations).

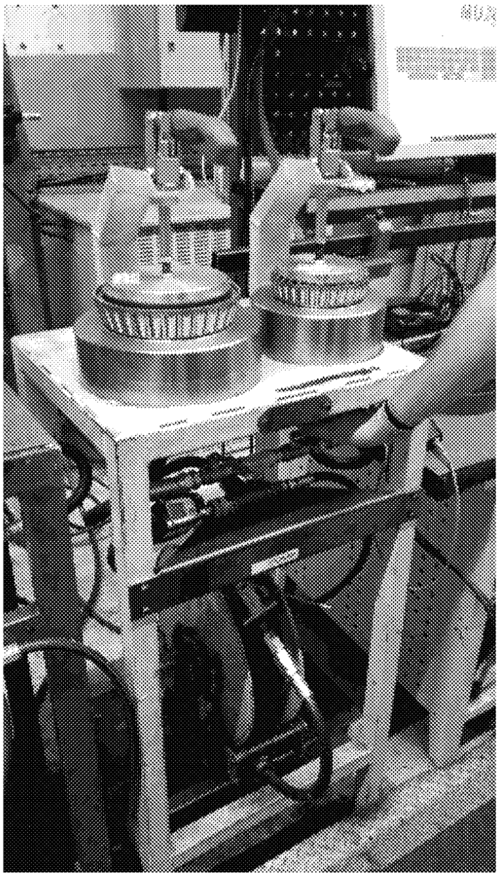


Figure 8. Process of hub bearings greasing at Texelis factory

5.2.2.5 Wrong fit of the inner ring

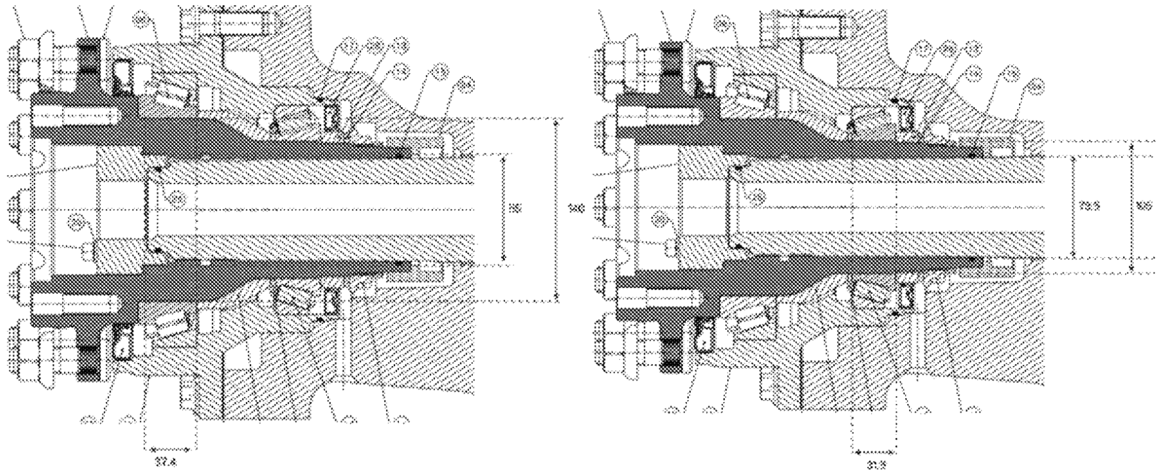
5.2.2.5.1 Loss of fit due to process

Hub assembly process comprises double fitting (fitting-remove-fitting) of the inner rings of the bearings. To study the influence of double fitting on the hub diameter and roughness the following test was performed by Texelis: a) measurement of hub diameter and surface roughness prior to mounting; b) double fitting of the inner rings of the hub; c) removal of inner rings and measurement of hub diameter and surface roughness. The results of the comparative measurements are given in the Table 1. The position of the bearings on the hub are shown on Figure 12.

We can state that the diameter dimensions did not change after double fitting, only the roughness has decreased as could be expected.

Table 3. Hub diameter before and after double fitting

Hub diameter	Nominal value	Measurement before fitting	Measurement after fitting
Small bearing position	105 p6	105,047	105,048
	R3,2	R1,15	R0,88
Large bearing position	140 p6	140,061	140,059
	R3,2	R2,15	R1,22

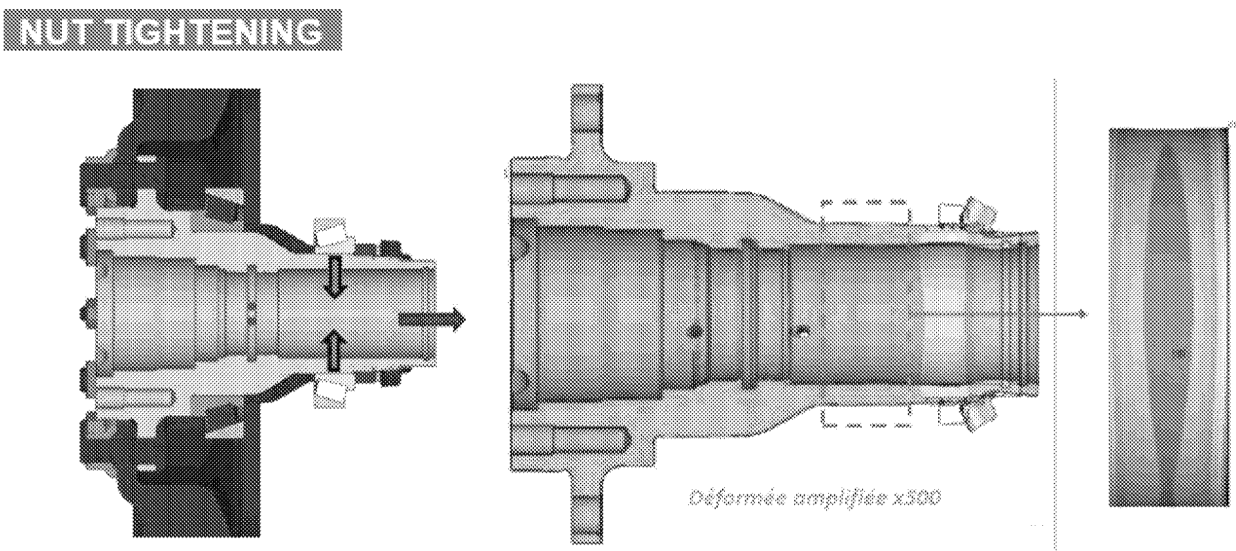


a) b)

Figure 9. Bearings position on the hub: a) large bearing; b) small bearing

5.2.2.5.2 Loss of fit due to design

The tightening of the retention nut leads to the elongation (" stretching") of the hub body resulting in the reduction of the diameter of the hub. This is illustrated on Figure X, *a*. That diameter reduction, in turn, could cause the loss of fit of small bearing inner ring. To verify this hypothesis finite-element calculations of the hub model were performed. These calculations showed that under nominal torque of the retention nut (tension force of 100 kN) the reduction of the hub diameter is of the order of 1-2 microns, Figure X, *b*. Considering that inner ring tight fit during the assembly comprises between 19 and 39 microns the calculated reduction of hub diameter due to nut tightening has a negligeable effect and is excluded from the possible root-causes.



a) b)

Figure 10. The effect of nut tightening on the hub: a) elongation of the hub body and subsequent diameter reduction; b) the reduction of hub diameter is of the order of 1-2 micron (blue area)

5.2.2.6 Re-elongation of the hub due to cold fitting of one flange

During hub assembly process audit at Texelis one area of concern was raised related to the cold fit of the flange within the hub. Prior to mounting the flange is cooled down in nitrogen to very low temperature and then installed on the hub. Cold flange cools down whole hub assembly. As no time is defined in the work instruction between assembly of the cold part in the hub and axial clearance measurement it could be possible that the axial clearance change when the hub temperature come back at ambient.

To check the influence of cold mounting on the axial clearance measurement the following test was performed on the newly assembling hub on Texelis production line:

- T0min: Cold mounting of the flange in the hub. Ambien temperature 18.4°C, hub temperature prior to mounting 17.6°C
- T12min: hub temperature 7.3 °C. Removal of the special tool of flange mounting
- T18min: Tightening of the retention nut (2000Nm/20°angle). Note: adjustment preload shim is installed.
- T23min: Start of axial clearance measurement. Hub temperature is 12.3°C
- T25min: End of axial clearance measurement. Registered clearance is 0,06mm
- T1h05: Hub temperature is 16.2 °C. Final torque tightening of the retention nut to 2017 Nm/21° angle
- T1h20: Axial clearance measurement on the hub (retention nut is not crimped). Registered clearance is 0,01 mm
- T8h27: Hub temperature is 18.1 °C Control of axial clearance: 0,01mm. Control of torque tightening: 2087 Nm with angle of 1.1°.

Performed test showed that cold mounting of the flange has no impact on the final axial clearance of the hub assembly.

Figure 11. Cold fit of the flange on the hub.

5.2.2.7 Wrong clearance setting (Push Pull test)

5.2.2.7.1 Test is done horizontally

Measurement of axial clearance of the assembled hub is done on a measurement stand by a push-pull + rotative press, Figure X. Axial clearance measurement is done in a horizontal position using a comparator. To verify the repeatability of the process the measurements were performed two times on the same assembly with similar results (0,06 mm). The work instruction precise that the measurement must be between 0,02mm and 0,08mm. The set-up shim was measured at 3,505mm by the worker. Then a measurement with the final shim of 3,477mm is done and the axial clearance is measured at 0,03mm, which is relevant with the shim reduction of 30µm.

The calibration report of the jack RV00017115-VERIN004 of the measurement stand dated 08/07/2021 states that the jack characteristics are conform – refer to Table X.

Table 4. Verification results of measurement stand jack (Calibration report N° 21 07 098)

Compression

Pt	Valeur nominale (N)	Valeurs mesurées (N)	Écart (N)	EMT (N)
1	1000	1015	15	± 50
		1018	18	
		1021	21	
		1017	17	
		1014	14	

Erreur maxi : 21 N

Traction

Pt	Valeur nominale (N)	Valeurs mesurées (N)	Écart (N)	EMT (N)
1	1000	1003	3	± 50
		1001	1	
		1005	5	
		1007	7	
		1004	4	

Erreur maxi : 7 N

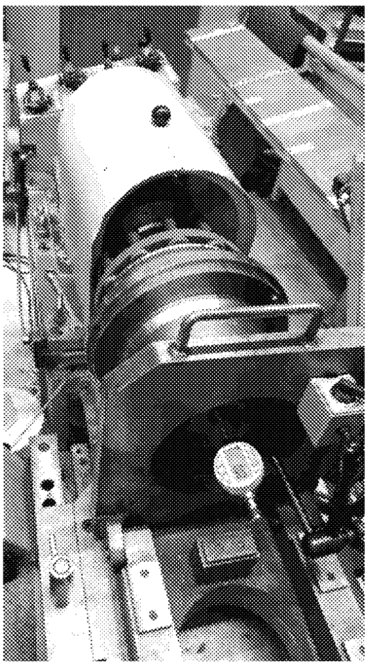


Figure 12. Stand for hub axial clearance measurement at Texelis factory

5.2.2.7.2 Wrong setting of shim calculation

The calculation of the shim setting during production is performed by Texelis Computer Assisted Production Management system (MUX). The operator enters the value of the adjustment shim, the value of measured clearance and MUX calculates the thickness of the definitive shim to achieve the required clearance of 0 +/-0,01mm.

5.2.2.7.3 Wrong setting of shim production

The operator disposes the set of pre-machined shims. The probability of producing a shim of wrong thickness seems to be low. Moreover, the shim of thickness considerably different than the thickness of the adjustment shim would be detected by the operator.

5.2.2.8 Conclusions from the Vendor Process Analysis

The conclusions from the vendor process analysis of the CBAs seems to exclude all the "people" and "Machine" related root causes.

5.2.3 Review of materials

5.2.3.1 Abnormal dimension

Waiting inner ring measurement results.

5.2.3.2 Embedding of one part

5.2.3.2.1 NOK Roughness

Design

The roughness of parts contributes to the settling losses of the bolted assembly. Roughness of each part corresponds to a certain value of creep, in microns.

The roughness of hub parts was taken into account in Texelis calculations in accordance with VDI2230. According to these calculations the settlement of roughness contributes to ~ 30% of the required tension of the assembly.

Parts roughness and corresponding creep values used in Texelis calculations are given in the Table X.

Table 5. Roughness and creep values of hub parts

	Ra on the drawing	Creep VDI (µm)
Hub	1.6	2
Bearing 32028	1.6	2
Spacer	0.8	2
Shim	1.6	2
Bearing 32021	1.6	2
Under-seal ring	6.25	2
Lock washer	1.6	2
Nut contact area	3.2	3
Nut thread	Quality 4H	3
Total creep according to VDI2230 (µm)		18

5.2.3.3 Quality

Waiting measurement results

5.2.4 Review of wheel flats

During the winter of 2019-2020 there were issues with excessive emergency brake events, which can lead to prolonged slides with no compensation, and wheel flats as a result. This issue was largely resolved by the following changes that were implemented over 2020 and January 2021.

- The ATC software was updated to better manage overspeed events moving into temporary speed restrictions
- The GIDS(Guideway intrusion detection system) software was changed to reduce the sensitivity to snow, and the elevation modified to reduce the number of emergency brake events.
- There were some rules established based upon the return of experience where the acceleration and brake rates of the system were modified based upon the weather conditions. Specifically:
  - in severe weather using "rate 2" (50% of normal motoring and braking rates) and
  - operation using "rate 1" (75% of normal motoring and braking rates) every morning, before 8:00am and every evening after 7:00pm, or at any time during the day, if the temperature fell below -11 degrees centigrade

These mitigations greatly reduced the number of EB events and wheel flats for the 2020-2021 winter.

There are several points to consider relative to the wheel flats and potential impact on the CBAs

- Given the mitigations put in place and the timing of those mitigations, compared to the timing of retrofit of the CBAs, the most severe impact of EB events and flats occurred before the retrofit of the CBAs, as a result the issues of the EBs would have impacted the old CBAs not the current fleet.
- Regardless of fleet configuration trains with noticeable flats were removed immediately from service and not allowed to return before reprofiling
- The maximum permissible flat to remain in service for wheel diameter sed on this train is in the order of 35-40 mm in length (EN 15313). Analysis of the lathe data, and assuming 100% of any radial run out was the result of a flat suggests that for LRV1119 the maximum flat on the configuration with the revised CBA was 20mm and within the permissible criteria and therefore should be within the design limits.

5.2.4.1 Conclusions from the review of wheel flats

As a result wheel flats are not considered to be a serious contributor to any issue regarding the CBA

5.2.5 The main line track

The main line of the LRT system operates with a frequency of trains past the point of derailment that is variable but on average has one train passage every 5 minutes. The track has had a history if issues from buckling in summer heat to rail breaks in the winter, along with corrugation in the high acceleration zones.

5.2.5.1 Track Maintenance History

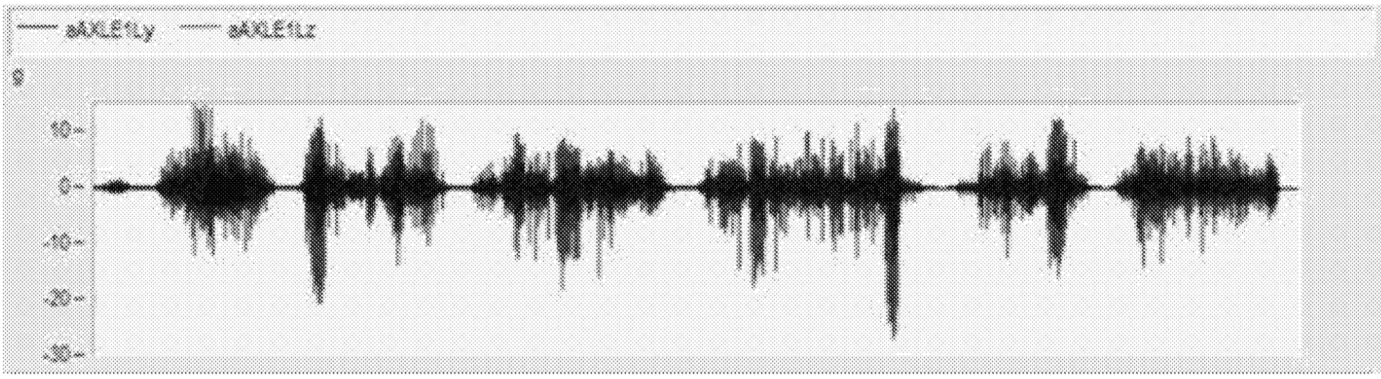
Summary of main issues on the track experienced since commencement of revenue service:

- Abnormal rail wear, with some curves wearing to >50% of maximum wear limit after 18 months of operation
- Severe corrugation observed on most curves after 1 year of operation
  - Grinding carried out in November 29th and 30th, 2020 on curves 230, 240, 280, 220. Severe corrugation found on these curves.
  - Tracks are "flat" in certain sections from LEE-BLR, as observed by grinding contractor in Nov. 2020. "*Flat rails are unlikely to have been worn to the level they are without some amount of grinding but without a history of rail profile measurements this is difficult to state with certainty. Flat rails also lead to more rapid corrugation growth due to more conformal contact between the wheel and rail.*"
  - Full system wide grinding carried out in July 2021.
  - Report from grinding contractor indicating that "*The severity and extent of corrugation on the Confederation Line within one year of operations suggests the vehicle/track dynamics and/or the wheel/rail interface are not performing in an optimized way.*"
- Surfacing issues experienced in first two years of operation:
  - Rail kinks appearing and reappearing at locations
  - Signs of tie movement in area between LEE and HUR
  - Surfacing and tamping campaign carried out in July 2021 in stretch of track between Blair and Uottawa
  - After surfacing activities in July 2021, rail kinks stopped in all locations where surfacing took place
  - Over 1000 tons of ballast dumped in July in stretch of track between Blair and Uottawa
- Severe vibrations levels experienced on the train, as noted by the February 2021 measurements that are in the following section.

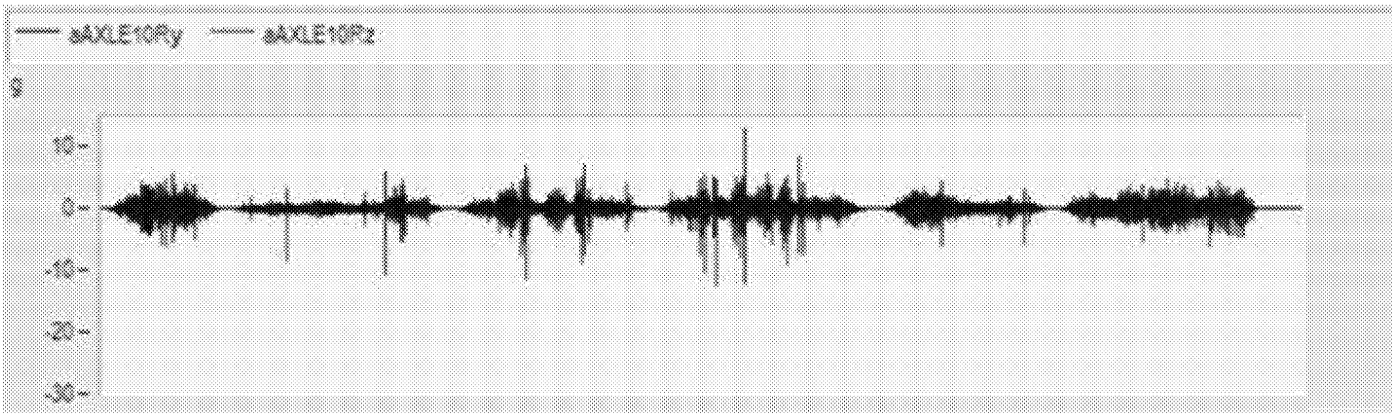
5.2.5.2 Vehicle vibration levels pre and post rail grinding

As part of an ongoing investigation into failures related to secondary bracketry on the bogies, there have been several measurement campaigns to quantify the vibration envelope for the bogies.

The charts below show the lateral (y axis) and vertical (Z axis) acceleration measured on the bogie axle beam over the alignment.



Axle Vibration Measured February 2021



Axle Vibration Measured August 2021

The surveys show that while there is an overall improvement, i.e. reduction in vibration induced from the track, there remain spots that still lead to higher than normal vibration.

5.2.6 Review of design load cases against analysis.

5.2.7 FEA Analysis

Note that the focus of the FEA analysis is to evaluate the reaction under loads and determine whether there is a possibility to lead to any rotating contact between parts, leading to contact wear and loss of preload on the assembly.

This is an ongoing process

5.2.7.1 Spacer deformation under load (bending of the hub)

According to finite-element calculations the deformation of the spacer (pos.10, Fig.3) under the load of 100 kN remains in its elastic zone (when external force is removed the spacer returns to its initial form). Thus, the behavior of the spacer resembles the behavior of the spring washer. This behavior is rather favorable for the hub assembly in the sense of participation to conservation of the assembly pretension.

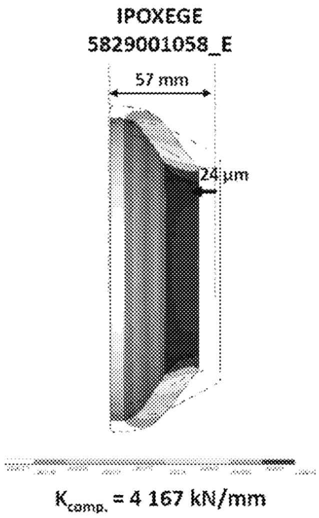


Figure 13. The deformation of the spacer under load of 100 kN

5.2.7.2 Overload from wheel to rail contact (curves, switch, wheel or track defects)

During the passage of the train in the curves considerable lateral forces are experienced by the wheelset (wheel flange pressed against the rail). These lateral curving forces could lead to bending of the hub and consequent axial and/or radial contact opening between the parts of the hub assembly illustrated on the Figure X.

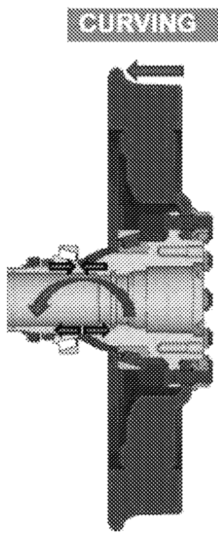


Figure 14. Influence of lateral force on the wheel hub

Complex finite-element model of the hub assembly was developed to evaluate the hub elements behavior due to lateral forces. In addition, a sensitivity analysis was applied on the lateral forces. The FE calculations demonstrated:

- Risk of axial contact openings (Figure X)
- Extension of the open contact when transversal load increases (Figure X)
- Contact pressure below the inner ring reduces when curve loads increase

Curves in OTTAWA present a transversal rail corrugation which potentially increase the risk of fretting corrosion.

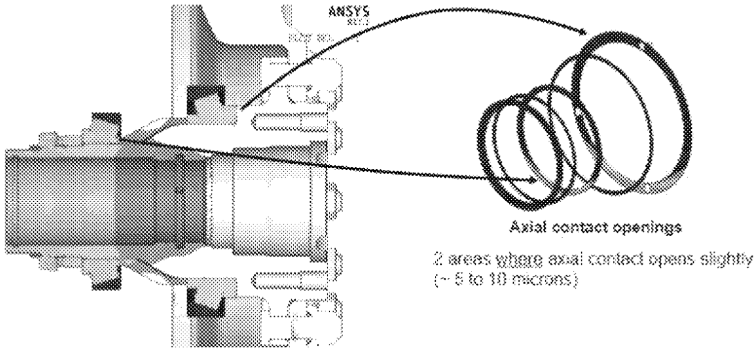


Figure 15. Areas of axial contact opening due to lateral curving forces

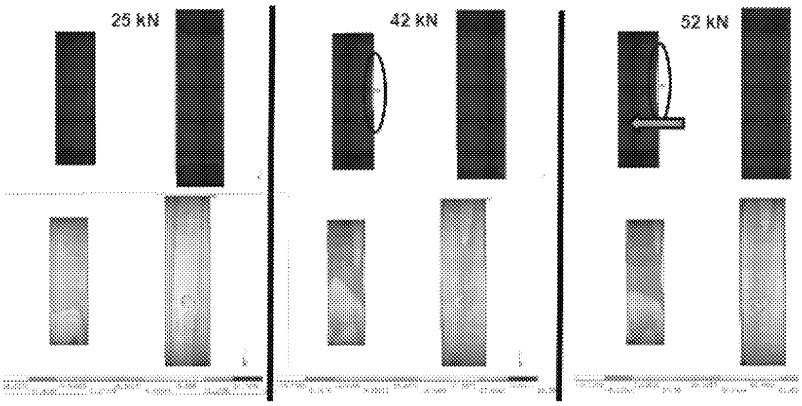


Figure 16. Extension of the open contact and reduction of contact pressure below the inner ring when transversal load increases

5.2.7.3 Overloads from the normal X,Y,Z acceleration of the bogie

Pres + essai en ligne en cours

5.2.7.4 Over torque from the motor

During the acceleration phase the torque of the traction motor is transmitted via gearbox to the axle beam hub. This torque induces a twist of the hub that could potentially lead to the reduction of the hub diameter under the inner ring. Hub assembly FE model similar to section 3.3.1.2 was used to evaluate the motor torque influence on the hub assembly. Combined vertical (10g) and lateral (5g) gearbox inertia was used in the model.

The FE calculations demonstrated:

- No opening of the axial contacts due to transversal inertia. Torque generated at the bearing much lower than generated through curves.
- Limited contribution of the Inertia loads due to the gearbox. However, due to rail corrugation, combined effect with the curve loads increasing the risk of fretting.

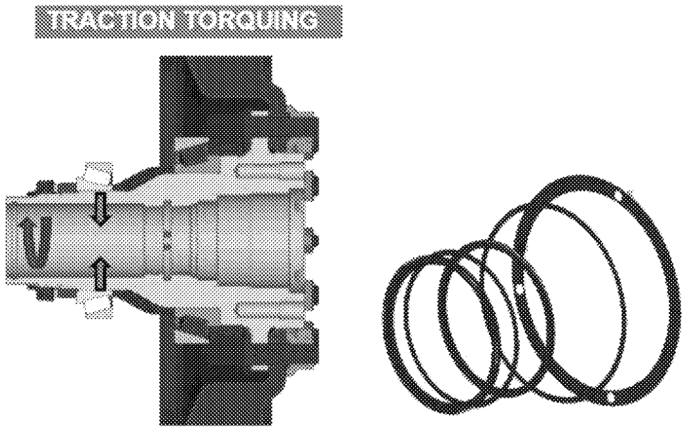


Figure 17. No contact opening due to traction torque

Pending

5.2.8 Track test campaign

Pending

6 SUMMARY, CONCLUSIONS & RECOMMENDATIONS

6.1 Summary

It is important to note that this is an interim report for an ongoing investigation, as a result, any interim conclusions are preliminary, and in most cases will be exclusionary, i.e. what we can exclude from the root cause, with a high degree of confidence.

It is also important to note that there is still work to be done.

6.2 PENDING ITEMS

Paragraph	Description	Expected date
5.2.1.3	Analysis of the metallic parts from LRV1118 hub teardown	30 Nov 21
5.2.1.4	Determination of the cause of mixed grease in the inboard bearing	
5.2.1.5	Materials analysis of the "soft materials" in the stack up on returned hubs, along with materials tests on the hubs and nuts.	
5.2.2.9	Awaiting dimensional analysis on parts used in the assembly	
5.2.2.9.2.2	Awaiting surface roughness analysis of parts used in assembly	
5.2.7	Completion of the FEA analysis	Dependent on Test track campaign
5.2.7.4	Completion of overload analysis in FEA modelling	Dependent on Test track campaign
5.2.8	Test track campaign to finalize the FEA analysis and modelling calibration.	1 Dec 21 (for installation of instrumented hubs)

6.3 interim Conclusions

To date, the analysis has eliminated supplier quality as an issue, both with respect to the human processes and the machines,

This is leading to a focus on materials, design loads, modeling and review of stresses present, and potential excess loads caused by the track.

REFERENCES

[P1]

Control Sheet

Version	Date	Content of Modification	Author(s)
A	2021-05-13	First issue.	L. Goudge / Train System Engineer Y. Liu / Project Engineering Manager