Proposed Findings and Recommendations

of

Kawasaki Rail Car, Inc.

as a Party to the Mechanical Group of the National Transportation Safety Board investigation into the

Derailment of Washington Metropolitan Area Transit Authority (WMATA) Metrorail Train

NTSB Accident No. RRD22LR001
Accident Date: October 12, 2021
Accident Location: Arlington, VA

Issue Date: February 27, 2023

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1. Overview of the Derailment

On October 12, 2021, WMATA train 407, consisting of eight 7000 Series railcars, was traveling southbound on track 2 of the Blue Line between the Rosslyn and Arlington Cemetery stations in Arlington, Virginia when one wheelset on the fourth car of the train, car no. 7200, derailed and did not re-rail. After the wheelset derailed, the train traveled about 1,800 feet before stopping in a tunnel. The NTSB determined that the point of derailment was in the frog of a turnout about 166 feet south of the Rosslyn station.

2. Findings

A. Background

1) <u>7000 Series Railcars and their Wheelsets</u>

Kawasaki Rail Car, Inc. ("Kawasaki") is the manufacturer of 7000 Series railcars, 748 of which were accepted by WMATA between February 2015 and May 2020. WMATA introduced the first 7000 Series train into passenger service in March 2015.

A wheelset is an assembly of two wheels (and other relevant parts) mounted on one axle. Wheelsets are assembled by pressing wheels inward onto their axle to achieve an "interference fit" between the slightly tapered ends of the axle and the inner bore of the wheels, which are tapered to mate. The interference fit that is achieved is a function of material, material dimensions, and mounting pressure (i.e., press-on force). The Association of American Railroads ("AAR") maintains industry standards for interference fit practices.

WMATA's design specifications required the linear distance between the back faces of wheels on an axle (the "gage" or "back-to-back") to be 53⁵⁄₁₆ inches ±¹⁄₁₆ inch. The ±¹⁄₁₆ inch tolerance does not represent a range of permissible wheel movement, but rather accounts for the permissible tolerances from wheelset to wheelset resulting from the assembly process, as well as a degree of imprecision inherent in the tools commonly used to measure gage.

During the immediate post-accident examination of car no. 7200, the NTSB found that the wheels of the derailed wheelset had moved outboard from their seats on the axle, increasing the gage beyond the design specification. This phenomenon is referred to as a "back-to-back failure" in this document. Kawasaki concurs with the NTSB's determination, upon further examination of the axle markings on the derailed wheelset, that the outboard movement of the wheels (by a total of 2 inches) was persistent and gradual over a period of time and not a sudden jump.

Wheels and axles were among the very few parts of the railcar for which WMATA supplied contract drawings and mandated their use. The wheelset design mandated for the 7000 Series was common with WMATA's 1000 Series, 2000 Series, 3000 Series, 4000 Series, 5000 Series and 6000 Series (hereafter collectively referred to as the "Legacy Fleets"). Kawasaki's own drawings for the 7000 Series railcar wheelset assembly, which were submitted to and approved by WMATA, accurately depicted the designs and specifications mandated for the wheels and axles. Further, Kawasaki's drawings indicated that the wheelsets would be pressed-on at 55-80 US tons, which matched the range of press-on force that WMATA used at the time for the Legacy Fleets (as instructed). After WMATA approved Kawasaki's wheelset assembly drawings in January 2013, Kawasaki proceeded with the approved design for pilot cars and mass production cars.

Four years later in April 2017, after the first two back-to-back failures were identified on 7000 Series railcars, Kawasaki was informed that: WMATA had experienced the same issue in its Legacy Fleets; a solution (viz., to increase the press-on force requirements to 65-95 US tons) was already approved for the Legacy Fleets; and implementation of the approved solution had resulted in no reoccurrences. WMATA asked whether Kawasaki could apply the approved solution to the 7000 Series wheelsets.

Kawasaki confirmed in May 2017 that the mounting force for the 7000 Series wheelsets could be increased to 65-95 US tons. Upon receiving this confirmation, WMATA instructed Kawasaki to proceed at the higher press tonnage requirements going forward. Subsequently, updated design drawings of the wheelset assembly were submitted to and approved by WMATA in July 2017. Also at that time, Kawasaki asked WMATA for instructions regarding the wheelsets that had already been manufactured to the original mounting requirements of 55-80 US tons, but received no reply. The first wheelset assembled at the higher-tonnage requirement was manufactured in October 2017 and installed on the 494th railcar out of 748 in the 7000 Series, which was accepted by WMATA in February 2018.

2) <u>7000 Series in Passenger Service</u>

Until March 2020, WMATA used railcars from the 2000 Series (76-car fleet), 3000 Series (282-car fleet), 6000 Series (184-car fleet) and 7000 Series (748-car fleet)—with the 7000 Series covering 65% of the mileage for the total mean distance between delays accumulated by all railcars during the period between July 2019 and March 2020. For the five months between March 16, 2020 and August 15, 2020 (during the COVID-19 pandemic emergency), to minimize delays that could lead to crowded conditions, 8-car 7000 Series trains were exclusively used due to the higher reliability of the 7000 Series. Although the 3000 Series and 6000 Series fleets were put back into service from August 16, 2020 (when WMATA implemented its COVID-19 Recovery Plan), the 7000 Series continued to comprise over 80% of the mileage, which eventually increased to 90% by September 2021 (in part because the entire 6000 Series fleet was taken out of service from November 2020 to August 2021 and was only gradually put back in service from September 2021). Thus, for well over 12 months preceding the derailment, 7000 Series railcars accumulated substantially more mileage than the Legacy Fleets.

3) <u>Reports of “Back-to-Back” Wheelset Failures</u>

Although Kawasaki has been designing and manufacturing railcars for customers around the world for over 100 years, Kawasaki has not previously experienced “back-to-back” failure to the best of its knowledge. In the course of this investigation, however, Kawasaki and NTSB learned that through 2021 WMATA had experienced back-to-back failures in 50 railcars of its Legacy Fleets (not counting Kawasaki’s 7000 Series railcars, but otherwise affecting at least one car in every single other Series), including nearly three dozen failures that WMATA identified in 2014.[1] WMATA had commissioned a consultant to conduct an investigation, resulting in a 2015 report which recommended, among other things, (i) increasing the press-on force / interference fit used for wheelsets, and (ii) further investigating any contributing effect of WMATA’s infrastructure (which was the only other commonality across all Series

[1] Additional back-to-back failures may have occurred prior to 2014, but WMATA does not appear to have records.

of railcars). It appears that WMATA subsequently began replacing original-tonnage wheelsets (i.e., 55-80 US tons) in the Legacy Fleets with higher-tonnage wheelsets (i.e., 65-95 US tons) when they came due for replacement in the ordinary course of maintenance. However, Kawasaki was not informed of either the problem or the solution at the time, and therefore proceeded to manufacture and deliver its 7000 Series railcars with wheelsets pressed at the original mounting tonnage.

In March and April 2017, WMATA reported to Kawasaki the first two instances of back-to-back failure on a 7000 Series railcar, which were discovered during normal periodic (90-day) maintenance inspections. As noted above, (i) it was at this time that Kawasaki learned that WMATA was already familiar with the issue and had implemented an approved solution in the Legacy Fleets (i.e., increasing the press-on force to 65-95 US tons), and (ii) Kawasaki began implementing the approved solution to the remainder of the 7000 Series order on a “cut-in” basis from October 2017. The third and fourth back-to-back failures were identified the next year, in January and February 2018, and another four instances were identified in January, March, April and October 2019. In all of these instances, Kawasaki replaced the wheelsets under warranty (with wheelsets pressed to the higher requirements) even though there was no indication that Kawasaki was responsible for the failures. The replacement wheelsets have not experienced recurrence of back-to-back failure.

As the post-COVID-19 proportion of 7000 Series mileage to total mileage expanded, WMATA reported a further five back-to-back failures in the 7000 Series, in February, April, May, August and December 2020. An additional 18 back-to-back failures were reported in 2021—including, for the first time, three that had been assembled at the higher “solution” tonnage range. Kawasaki replaced those wheelset assemblies that were still under warranty at that time, while WMATA replaced the remainder using their stock of wheelset assemblies. To our knowledge, the replacement wheelsets (whether or not supplied by Kawasaki) have not experienced recurrence of back-to-back failure to date.

In the immediate aftermath of the October 2021 derailment, WMATA conducted a special “blitz” inspection of the entire 7000 Series fleet (i.e., not just the cars due for 90-day inspection) for compliance with gage specifications, which resulted in the discovery of more, previously unreported, back-to-back failures. After some initial over-reporting, it was ultimately determined that there were 20 additional failures (for a total of 51 failures since inception).

B. Wheelset Tear-downs

Shortly after commencement of this investigation, Kawasaki observed the following tests and inspections conducted by the other investigation parties on wheelsets that had experienced back-to-back failure.

1) Wheel Demounting Test – Purpose of which was to measure the demounting force and to inspect dimension of the wheel seat and the wheel bore.
2) Spin Test – Purpose of which was to spin the wheelset on a test rig independent of other components of the trucks to measure accelerations at predetermined locations on the wheelset.
3) Gear Unit Tear-Down – Purpose of which was to measure backlash and axial play and to inspect inner parts of the gear unit.
4) Journal Bearing Tear-Down – Purpose of which was to measure the demounting force and to inspect each dimension.
5) Metallurgical Test of #7200 derailment wheel axle – Purpose of which was to review details of the wheel and axle for materials properties, hardness, microstructures, surface conditions, metallography, etc.

None of these tests and inspections uncovered irregularities or other conditions that could potentially contribute to the derailment analysis.

C. Running Test

In June 2022, in its role as a party to this investigation, Kawasaki conducted a "running test" using 7000 Series railcars specially equipped with instruments to measure vibration, thermal, axle stress, wheel forces, etc. Kawasaki considers that all measurements, except wheel outward lateral forces, were normal and did not correlate to wheel migration. On the other hand, significant outward lateral forces were measured many times in the running test, including values that appeared unusual in Kawasaki's experience. Therefore, Kawasaki has focused on the wheel outward lateral force.

Tables 1 and 2 below show the occasions when significant wheel outward lateral forces (i.e., more than 50kN) were observed during the running test (on mainline tracks and railyard tracks, respectively). They show that the significant outward lateral forces occurred at either turnouts or crossovers, and almost all affected the left (i.e., gear side) wheel. These issues will be addressed below.

Table 1: Summary of Outward Lateral Force Measured in Mainline

Summary of Outward Lateral Force Measured in Mainline												
Date	Line	Data #	Lateral Force [kN]		Speed	ChainMarker	Location					Description
			L-Side	R-Side	[MPH]	[100feet]						
2022.06.15	Silver	SV#11	62	17	43	271.13	D08	Stadium-Armory	→	G01	Benning Road	No.8 Turnout (Around D&G Junction)
(Day)			71	18	43	271.83						
			60	24	43	271.85						
			53	18	43	271.86						
		SV#16	72	18	36	86.51	D05	Capital South	→	D04	Federal Center SW	No.8 Double Crossover
			61	25	31	-6.14	C01	Metro Center	→	C02	McPherson Sq	Left Hand Curve with Restraining Rail
			70	18	31	-11.75						Left Hand Curve with Restraining Rail
			69	16	36	-221.30	K01	Court House	→	K02	Clarendon	No.8 Double Crossover
2022.06.16	Red	RD#13	94	2	51	354.27	B07	Takoma	→	B06	Fort Totten	No.8 Single Crossover
(Day)			115	-19	51	354.24						No.8 Single Crossover
			53	28	51	259.54	B06	Fort Totten	→	B05	Brookland-CUA	No.10 Single Crossover
			67	9	27	-71.34	A03	Dupont Circle	→	A04	Woodley Park-Zoo/Adams Morgan	
		RD#15	63	1	22	-939.21	A15	Shady Grove	→	A14	Rockville	No.10 Double Crossover
			78	21	43	255.67	B05	Brookland-CUA	→	B06	Fort Totten	No.8 Guarded Turnout
			60	10	39	636.63	B10	Wheaton	→	B11	Glenmont	No.8 Double Crossover
2022.06.17	Yellow	YL#12	54	15	25	53.79	C07	Pentagon	→	F03	L'Enfant Plaza	No.15 Turnout
(Day)			6	50	38	-135.50	E04	Columbia Heights	→	E05	Georgia Ave-Petworth	Right Hand Curve with Restraining Rail
		YL#14	53	16	26	53.80	C07	Pentagon	→	F03	L'Enfant Plaza	No.15 Turnout
			16	57	22	-659.45	E09	College Park-U of Md	→	E10	Greenbelt	No.10 Double Crossover
2022.06.17	Orange	OR#22	60	24	18	-527.50	K07	Dunn Loring-Merrifield	→	K06	West Falls Church-VT/UVA	No.8 Double Crossover
(Day)		OR#24	54	-6	25	-774.21	K07	Dunn Loring-Merrifield	→	K08	Vienna/Fairfax-GMU	No.10 Double Crossover
2022.06.20	E-Line	E#12a	53	29	19	-93.12	E04	Columbia Heights	→	E03	U Street	Left Hand Curve with Restraining Rail
(Night)		E#13a	58	29	30	-93.12	E04	Columbia Heights	→	E03	U Street	Left Hand Curve with Restraining Rail
		E#14a	58	28	30	-93.12	E04	Columbia Heights	→	E03	U Street	Left Hand Curve with Restraining Rail
		E#15a	62	28	37	-93.12	E04	Columbia Heights	→	E03	U Street	Left Hand Curve with Restraining Rail
		E#16a	63	27	38	-93.13	E04	Columbia Heights	→	E03	U Street	Left Hand Curve with Restraining Rail
		E#17	59	22	37	-93.12	E04	Columbia Heights	→	E03	U Street	Left Hand Curve with Restraining Rail
2022.06.26	C-Line	C#22a	52	9	39	-146.78	C06	Arlington Cemetery	→	C05	Rosslyn	No.15 Turnout
(Night)		C#23a	53	11	22	-186.97	C06	Arlington Cemetery	→	C05	Rosslyn	No.8 Guarded Double Crossover
2022.06.28	Green	GR#13	56	-8	24	-659.31	E10	Greenbelt	→	E09	College Park-U of Md	No.10 Double Crossover
(Day)	(AW2)		64	19	37	-93.62	E04	Columbia Heights	→	E03	U Street	Left Hand Curve with Restraining Rail
2022.06.30	Green	GR#22	52	15	25	536.72	F11	Branch Ave	→	F10	Suitland	No.10 Double Crossover
(Day)	(AW0)	GR#24	52	10	27	-658.30	E10	Greenbelt	→	E09	College Park-U of Md	No.10 Double Crossover
			60	24	34	-93.60	E04	Columbia Heights	→	E03	U Street	Left Hand Curve with Restraining Rail
2022.06.30	Yellow	YL#22	64	17	26	57.71	C07	Pentagon	→	F03	L'Enfant Plaza	

Table 2: Summary of Outward Lateral Force Measured at Yard

Summary of Outward Lateral Force Measured at Yard							
Date	Data #	Max. Lateral Force [kN]		Speed	ChainMarker	Location	
		L-Side	R-Side	[MPH]	[100feet]		
2022.06.16 (Day)	RD#13	80	43	9	N/A	A99	Shady Grove Yard
2022.06.17 (Day)	YL#10a	71	32	11	N/A	K99	West Falls Church Yard
2022.06.30 (Day)	GR#23	40	70	12	N/A	E99	Greenbelt Yard

Kawasaki has ample experience in measuring forces on wheels during running tests, as in this case. Maximum outward lateral force measured in another running test of a similarly-sized vehicle was approximately 30kN to 40kN. As shown above, significant outward lateral forces exceeding 50kN were frequently generated in the running test, with the highest value reaching 115kN.

D. Micro-Slippage

As noted above, post-derailment examination of the derailed wheelset showed signs of a gradual, incremental outboard migration of the wheels from their seats on the axle. Reports and scientific studies about previous back-to-back failures in the passenger rail industry suggested that the axle markings were indicative of accumulation of "micro-slips," a phenomenon in which outward lateral force applied repeatedly to the wheel flange back causes wheels to migrate along the axle in microscopic increments, even if the outward lateral force is only 10% to 20% of the wheel mounting force.

In its role as a party to this investigation, Kawasaki investigated whether accumulation of micro-slips could explain the back-to-back failures observed in 7000 Series railcars. As detailed below, Kawasaki has concluded that such accumulated micro-slippage is the mechanism by which otherwise adequately seated wheels moved laterally on their axles, and that such repetitive micro-slippage was most likely caused by excessive outward lateral forces exerted by elements within WMATA's track infrastructure.

E. Evaluation of Probable Root Cause

1) <u>Materials and Workmanship Not Implicated</u>

The derailment investigation turned up no evidence of defective materials or workmanship in the derailed wheelset or other 7000 Series wheelsets that had been identified as exhibiting back-to-back failure. To the contrary, records and testing during the investigation demonstrated that the derailed wheels and axle, and their assembly process, fully complied with all applicable technical specifications at the time of assembly. Kawasaki notes further that defects in materials and/or workmanship of 7000 Series wheelsets, if any, could not possibly explain the historical occurrence of back-to-back failures in the Legacy Fleets.

Accordingly, Kawasaki believes that the root cause of the October 2021 derailment is not a matter of defective materials or workmanship relating to wheels, axles, or assembly, all of which may be confidently ruled out as contributing factors.

2) <u>Excessive Outward Lateral Forces Exerted by Certain Infrastructure</u>

Comprehensive data on the number and other characteristics of back-to-back failures in the 7000 Series has been collected, but the record for the Legacy Fleets is incomplete—the data does not appear to exist from any time prior to 2014. What is clear, however, is that back-to-back failures have been recorded in every single Series of railcar used by WMATA. There are only two elements in common among all Series of railcars used by WMATA at any time: (1) wheelset design, and (2) track infrastructure.

Kawasaki believes that the back-to-back failures observed in 7000 Series railcars (and likely in Legacy Fleets railcars as well) were caused by the accumulation of "micro-slips" resulting from previously unsuspected significant outward lateral forces repetitively exerted by certain guardrails and restraining rails upon the back faces of wheel flanges.

i) FEA Modeling of Outward Lateral Force Effects on Micro-Slippage

The mechanism of wheel migration caused by micro-slip accumulation is explained below for the two cases in which significant outward lateral force was observed in the running test:

- Impulsive Force, measured near the mainline turnout and crossover, and
- Continuous Force, measured in the yard.

- **Impulsive Force**

The color contour in Figure 1 shows the relative displacement between a wheel and its axle using the finite element analysis (FEA) model. Negative numbers (blue and green) show outward displacement, positive numbers (red and orange) show inward displacement, and yellow shows no movement.

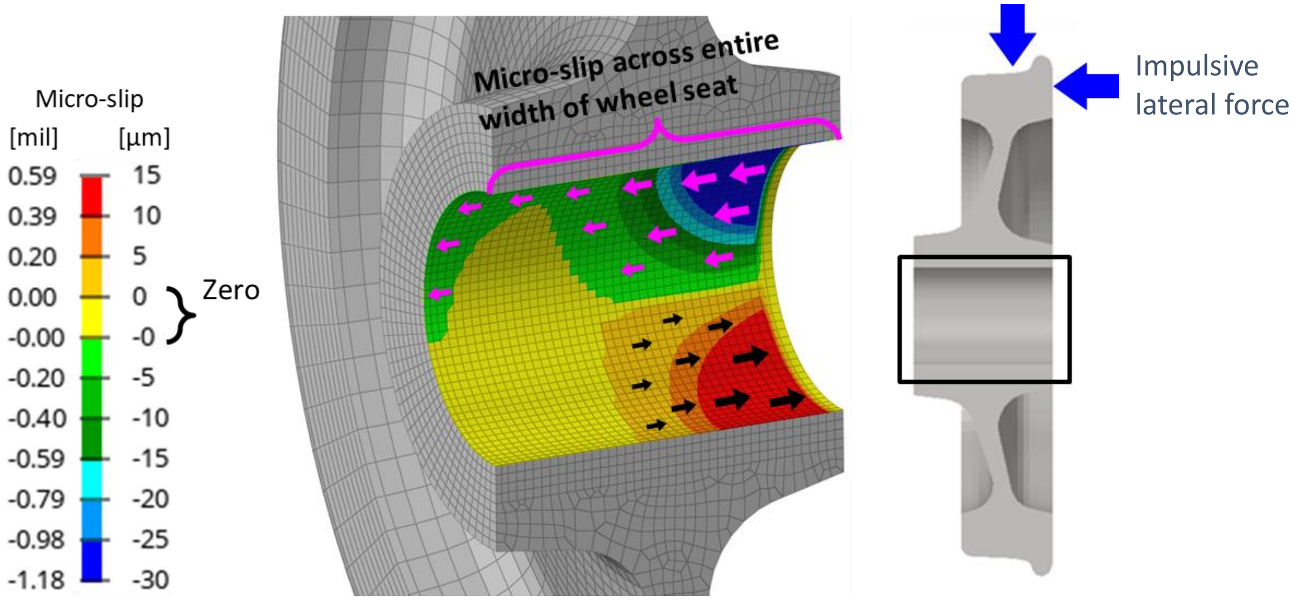

Figure 1: Relative Displacement Between Wheel and Axle

Under zero loading conditions, one would expect the entire expanse of the wheel seat to be shown in yellow, above. Kawasaki found that under impulsive force conditions, outward displacement forces run across the entire width of the wheel seat (i.e., replacing yellow with unbroken blue/green from face to face, albeit not necessarily across the entirety of the seat at any one time). Thus, when significant impulsive outward lateral force is applied to the wheel flange back, micro-slippage occurs across the entire width of the wheel seat along some arc of the axle/seat interface. If the micro-slip across the entire width of the wheel seat transits often enough through the full circumference of the axle/seat interface as the wheel turns, the accumulation may eventually result in a gradual, progressive migration of the wheel along the axle.

Under actual running conditions, significant outward lateral forces are applied at random angles as shown in Figure 2. The pink band represents micro-slip accumulation.

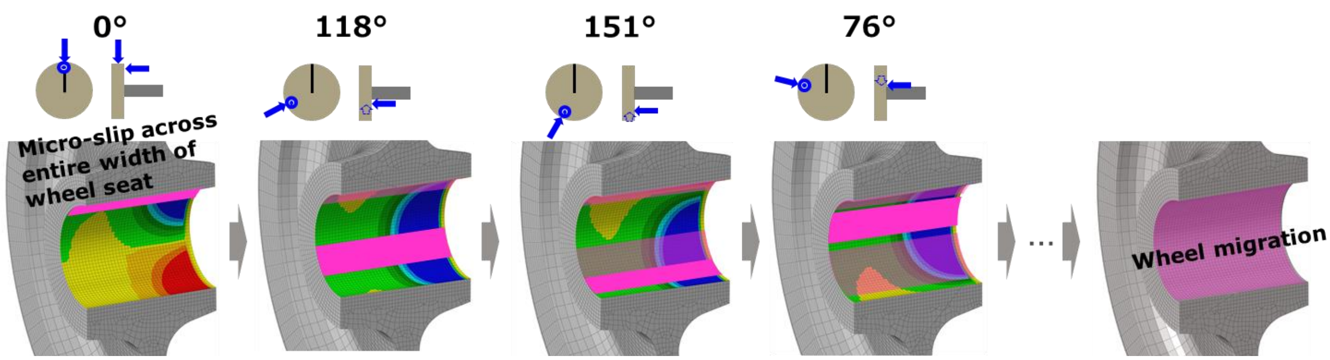

Figure 2: Outward Lateral Forces Applied at Random Angles

- **<u>Continuous Force</u>**

According to the running test results, the bending stress on an axle is increased when a continuous outward lateral force is exerted on the wheel, such as from a restraining rail. A schematic representation of that situation is shown as Figure 3.

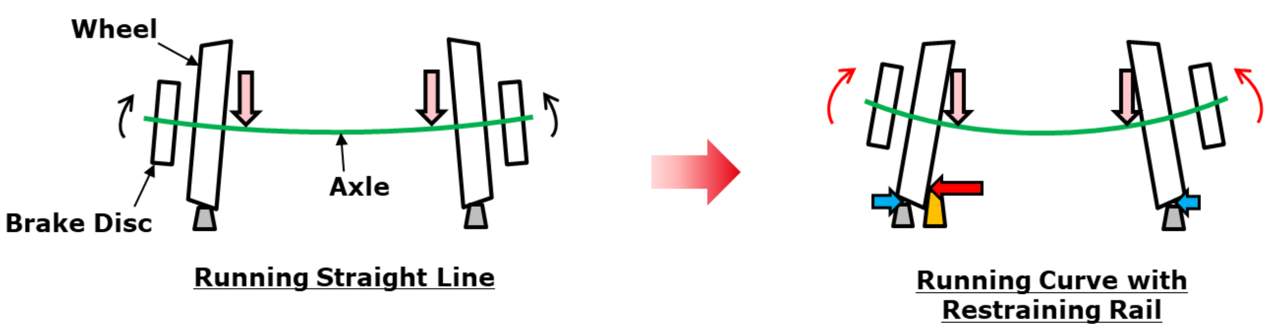

Figure 3: Schematic Representation of Bending Stress on Axle

Since the 7000 Series truck is what is known as an inboard truck frame type, the axle load is applied between the wheels, which causes the axle to bend convex downward. The restraining rail comes into continuous contact with the flange back of the inner wheel when the railcar runs on a curve, which increases axle bending. The continuous force (i.e., axle bending) condition requires less outward lateral force to cause micro-slippage to occur across the wheel seat than in the case of impulsive force.

For reference, please view the FEA animations linked to this document, of two continuous force cases. FEA Animation Case 1 illustrates a condition where force is applied continuously but does not reach the Critical Lateral Force[2]. The areas represented in yellow are areas where no relative displacement occurs. FEA Animation Case 2, on the other hand, illustrates a condition where a larger continuous force is applied than in FEA Animation Case 1. In this case, however, when the applied force exceeds the Critical Lateral Force, the area represented in yellow (where no relative displacement occurs) is lost in the first

[2] "Critical Lateral Force" means the threshold amount of outward lateral force at which micro-slippage across the entire width of the wheel seat occurs.

cycle. The graphs in Figures 4 and 5 also shows a difference in wheel migration behavior. At least some wheel migration occurs within a few revolutions when Critical Lateral Force is reached in cases of continuous force.

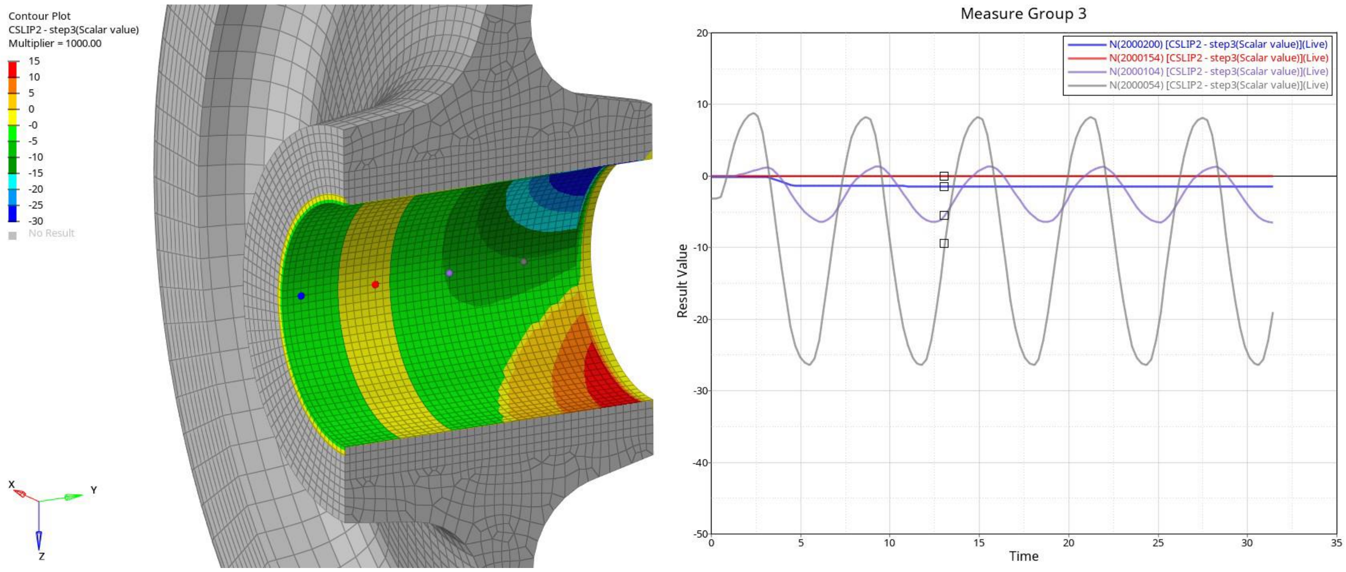

Figure 4: FEA Animation Case 1 – No Wheel Migration
(animation can be viewed by clicking on figure)

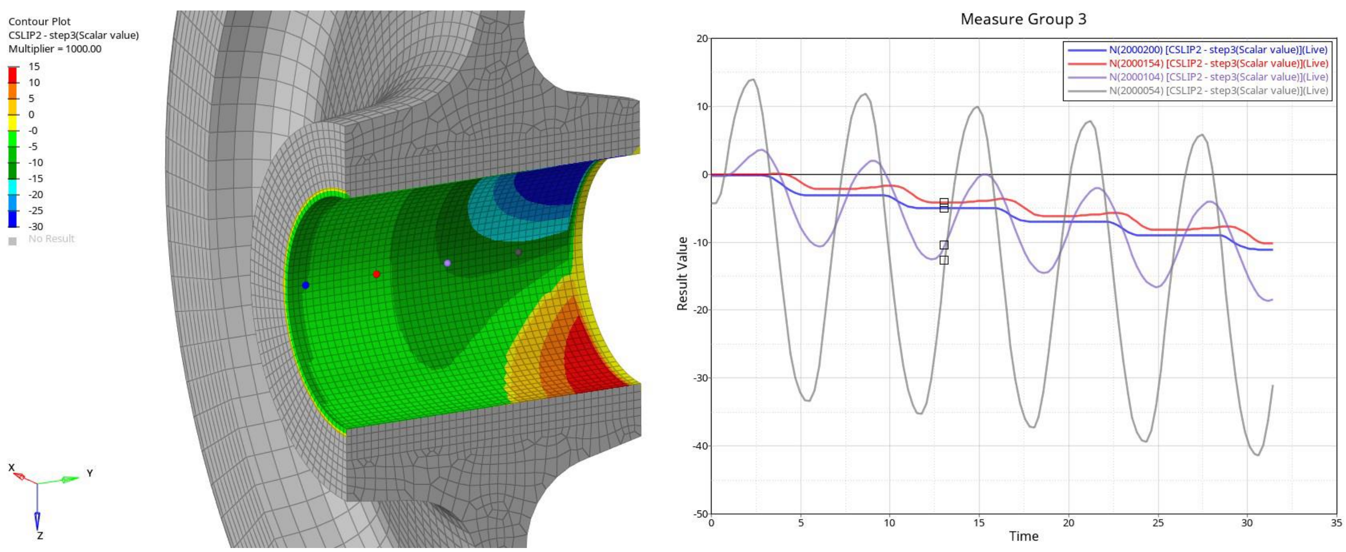

Figure 5: FEA Animation Case 2 –Wheel Migration
(animation can be viewed by clicking on figure)

ii) <u>Validation of FEA Model By Observed Data</u>

As part of its investigation, Kawasaki conducted a test to reproduce wheel migration using an actual 7000 Series wheelset, the purpose of which was to identify the relationship of Critical Lateral Force to wheel press-on force. In this test, wheel migration occurred (i.e., Critical Lateral Force was reached) when outward lateral force of approximately 17% of the wheel mounting force was applied to the wheel flange back. The result was confirmed to be consistent with the FEA results.

In addition, Table 3 shows the "Critical Lateral Force" ranges, as calculated using the FEA model, at each wheel press-on force within AAR guidelines for WMATA-mandated wheels and axles.

Table 3: Press-on Force and Critical Lateral Force Range

	Press-on force [US ton]	Critical Lateral Force Range [kN]	
		Impulsive	Continuous
1% < Failure Rate	**55**	**88 – 94**	**63** – 70
	60	**96 – 102**	69 – 76
0% < Failure Rate ≤ 1%	**65**	**104 – 111**	75 – 82
	70	**112** – 119	81 – 88
	75	120 – 128	87 – 95
Failure Rate = 0%	**80**	127 – 136	92 – 101
	85	135 – 145	98 – 107
	90	143 – 153	104 – 114
	91	145 – 155	105 – 115
	95	151 – 162	110 – 120

The percentages shown at the left side of the table (i.e., "1% < Failure Rate", "0% < Failure Rate ≤ 1%" and "Failure Rate = 0%") are actual back-to-back failure rates observed on the 7000 Series wheelsets. Where back-to-back failure actually occurred, the wheels had been pressed on with forces in the ranges marked in red and yellow (i.e., the press-on force was less than 80 US tons). Wheel migration was not observed in the range marked in blue. Corresponding Critical Lateral Force numbers are highlighted in red where less than the maximum lateral forces measured during the running test.

- Impulsive Force: 115kN (Measured near the mainline crossover)
- Continuous Force: 64kN (Measured in the yard)

The actual outward lateral force exerted on any given wheelset will depend on track conditions, which changes day-by-day, as well as train operation factors. The maximum outward lateral force observed in Kawasaki's running test in June 2022 was 115kN. It should be noted that if outward lateral forces are measured again, it is possible that even higher values may be observed as they are highly dependent on the track condition. It should be further noted that the measured impulsive forces and the actual back-to-back failure rate observed are in consistent with the results of the FEA (as summarized in Table 3).

In addition, Table 3 shows that if the outward lateral force is a normal magnitude that Kawasaki has experienced before elsewhere (i.e., 30kN to 40 kN), wheel migration does not occur even with wheels pressed at the original mounting requirements (i.e., press-on force of 55-80 US tons).

Most railway operators in Japan have adopted the Japanese Industrial Standards for wheel press-on force (JIS E 4504), and to Kawasaki's knowledge they have experienced no cases of wheel migration. If the press-on force used at WMATA is calculated in accordance with JIS E 4504, it would be equivalent to 54.2 to 92.6 US tons, which is not significantly different from the tonnage originally used on the 7000 Series. Therefore, based on its experiences in Japan, Kawasaki considers the original 7000 Series press-on force to have been appropriate, assuming that unusual outward lateral forces would not be an issue.

3) Explanation of Specific Phenomena

i) Wheel Migration Occurring Predominantly on the Left (Gear Side) Wheel

It was noted that most of the wheel migration occurred on the left (gear side) wheel. According to the running test results using the 7000 Series, almost all the significant outward lateral forces were measured on the left wheel and the measured locations were either turnouts or crossovers. Kawasaki investigated this phenomenon and believes that it can be explained as follows:

- Generally, wheel lateral forces are higher on the leading axle than the trailing axle.
- The gear unit on the leading axle is always located at the left-hand side.
- Turnouts and crossovers in the mainline are located in the left-hand side because the train is always running on the right-hand track.

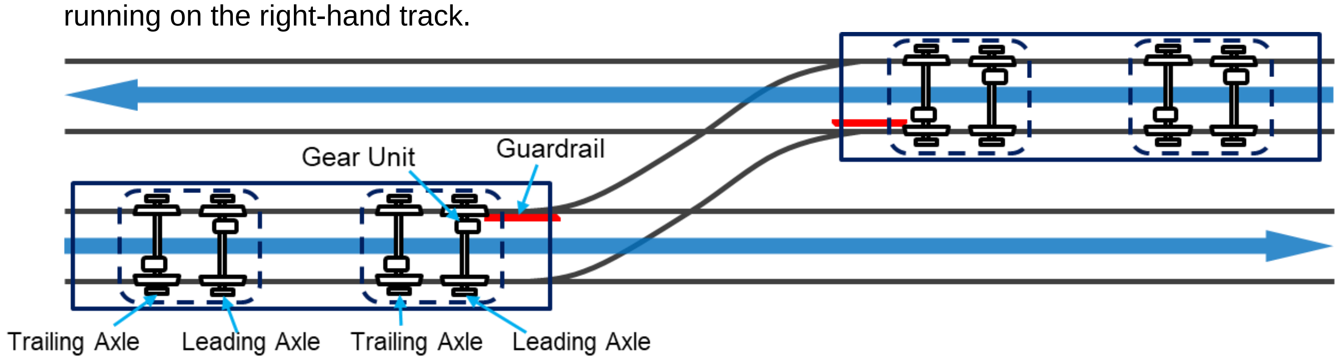

Figure 6: Relationship of Guardrail, Axle/Gear Unit and Train Direction

Furthermore, after investigating the running test results in detail, Kawasaki has noticed that when moving straight through turnouts or crossovers (i.e., not crossing over to the other track), the flange back of the left wheel hits the guardrail/restraining rail located near the turnout or the crossover. Because of the high speed when travelling straight at the turnout/crossover, significant impulsive force is likely applied to the wheel flange back.

For these reasons, Kawasaki is of the opinion that most of the wheel migration occurs on the left (gear side) wheel because the significant impulsive force causing migration is predominantly applied to the left wheel flange back.

ii) Marked Increase in 7000 Series Back-to-Back Failures, 2020 vs. 2021

Kawasaki believes that, since even before the start of the COVID-19 pandemic, WMATA's Metrorail operations relied heavily on the 7000 Series due to its higher reliability compared to the Legacy Fleets. This circumstance resulted in exposure to both impulsive and continuous forces over the extended mileage needed for the accumulation of micro-slippage that manifested as wheel migration largely in 2021.

iii) Relative Incidence of Back-to-Back Failures, 7000 Series vs. Legacy Fleets

In the course of the derailment investigation, some have asked whether an apparently higher incidence of back-to-back failures in the 7000 Series fleet, compared to the Legacy Fleets, is attributable to some unique characteristic of the 7000 Series. In particular, it has been proposed that car/truck vibration may explain the difference.

As an initial matter, Kawasaki notes that it has not been established that the 7000 Series has in fact exhibited a higher relative incidence of back-to-back failures. It is simply not possible to definitively state that the number of back-to-back failures is higher for the 7000 Series (much less, meaningfully so) given that a complete record of back-to-back failures in the Legacy Fleets (or even of similar issues that could have been reported *in lieu* of back-to-back failures) does not exist. For all anyone knows (or will ever know), the historical incidence of back-to-back failures in any or all of the other Series in WMATA's railcar fleets could be the same or higher than was recorded for the 7000 Series. Moreover, even if it were true that the 7000 Series has had the highest number of back-to-back failures, it would also be true that the 7000 Series fleet has not only the highest number of cars but also the highest total mileage (as of October 2021). In short, there is little if any basis for the premise that there is a phenomenon in need of explanation.

As a further matter, Kawasaki does not believe that car/truck vibration can be a viable explanation for any degree of wheel migration for the simple reason that, while one could expect the effects of such destructive vibration to manifest in numerous other (less robust) components of the railcar before affecting wheelsets, none have been observed. Indeed, investigation (by other parties) into car/truck vibration in 7000 Series railcars (and 3000 Series railcars) has generated no quantitative evidence that it either causes or contributes in any way to wheel migration.

Accordingly, Kawasaki concludes that the root cause of the October 2021 derailment is the accumulation of micro-slips resulting from significant outward lateral forces repetitively exerted by certain guardrails and restraining rails upon the back faces of wheel flanges.

3. Recommendations

Through the running test results and the detailed investigative study, Kawasaki has found that the outward lateral force on the wheel flange back is the only aspect of WMATA's operation of 7000 Series railcars that is clearly different from other railway operators. In addition, it was confirmed by the FEA model and testing using actual wheelsets that wheel migration is caused by frequent loading of significant outward lateral force on the wheel flange back.

Fundamentally, in order to prevent this wheel migration from occurring, the cause of the significant outward lateral forces must be eliminated. The investigation found that significant outward lateral forces were measured at infrastructure locations where guardrails and restraining rails are installed on the track, especially near turnouts and crossovers.

Thus, it is Kawasaki's recommendation that guardrails and restraining rails should be reset, especially near turnouts and crossovers, in order to reduce the outward lateral force that would adversely impact the wheelsets of the railcars running through them.

Practically, however, it may not be feasible to reset all guardrails and restraining rails. As an alternative—albeit potentially less effective in entirely eliminating wheel migration—the wheel press-on force should be increased to a range more likely to overcome the lateral forces exerted by the guardrails and restraining rails. Specifically, the lower limit of the wheel press-on force range should be increased to no less than 80 US tons so that the wheelsets are manufactured to be in the blue range shown in Table 3 above.

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