National Transportation Safety Board

Office of Railroad, Pipeline and Hazardous Materials

Washington, DC 20594

RRD24MR002

MECHANICAL

Group Chair's Factual Report

1/20/2024

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A ACCIDENT

Location: Chicago, Illinois
Date: November 16, 2023
Time: 10:30 a.m.

Train: CTA 5599/5600 and S-500 Snow Machine

B MECHANICAL GROUP

Group Chair	John Manutes NTSB Denver, Colorado
Group Member	Grant Macey CTA Chicago, Illinois
Group Member	Steve Giguere Alstom Montreal, Canada
Group Member	Christian Roy Alstom Montreal, Canada

C SUMMARY

See the IIC synopsis in the docket for this accident for a summary of this accident.

D FACTUAL INFORMATION

1.0 Striking Train

The striking train was designated as "Run Number 593" on the CTA Yellow Line, also known as "The Skokie Swift". The train consisted of two cars, semi-permanently coupled together.[1] The lead car was number 5599 and the trailing car was 5600. The cars were semi-permanently coupled at each car's No. 2 end position, with operating cabs on the No. 1 ends. The cab of car number 5599 was occupied by a CTA operator, and the rear-facing cab of car number 5600 was not occupied.

Both cars were built in 2014 by Bombardier Transportation, now Alstom, as a part of a total order of 714 vehicles from 2009-2015. Each car has seated and standing positions for passengers and nine security cameras per car.

The 5000-series cars operate with a nominal line voltage of 600 volts DC which powers four AC traction motors. The carbody is stainless steel. The truck is a welded steel frame with inboard bearings. Braking is accomplished through dynamic braking, hydraulic friction braking, and magnetic track brakes. Each car is 48-feet long with a maximum exterior width of 9-feet 4-inches. At the floor level, the car width is 8-feet 8-inches. The car operates on standard gauge (4-feet 8.5-inches) track with a truck center distance of 33-feet 8-inches. New wheels have a nominal diameter of 28-inches. The delivered empty car weight (AW0) of 5599 was 54,802lbs and 5600 was 54,785lbs .[2] The full design capacity (AW3, seated and standing) is 80,100lbs. The total capacity of the train is 132 passengers including 38 total seats per car.[3]

The car's designed buff strength is 200,000 pounds. The maximum design speed is 70 mph. Full-service braking is designed to accomplish a deceleration rate of 2.8 mphps. The designed emergency braking rate is 5.3 mphps + track brake effort.[4]

For this report, the orientation of the vehicles in terms of front, back, left, and right will be determined by the direction of travel. This may be different than CTA nomenclature. If specific locations are referenced, such as 'No. 1 End', CTA locations

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[1] Semi-permanently coupled refers to two individual car units which are coupled together by a drawbar that cannot be disconnected without specialized tools and are only disconnected in a designated maintenance facility.
[2] The 5000-Series maintenance manuals list a max empty design weight of 57,000 lbs. The car history book for each car is a more accurate representation of the "delivered" empty weight and are used above.
[3] The 5000-series maintenance manuals have a typo for total capacity. The actual total capacity is 132.
[4] The brake rate design tolerance is +/- 0.1 mphps. There is a small discrepancy between the maintenance manual and the design specification (5.1 mphps vs. 5.3 mphps) for this reason. The 5.3 mphps number is used in the design specification and qualification test reports and is used here for that reason.

will be used. These designations may differ from CTA or manufacturer designations. See the figure below.

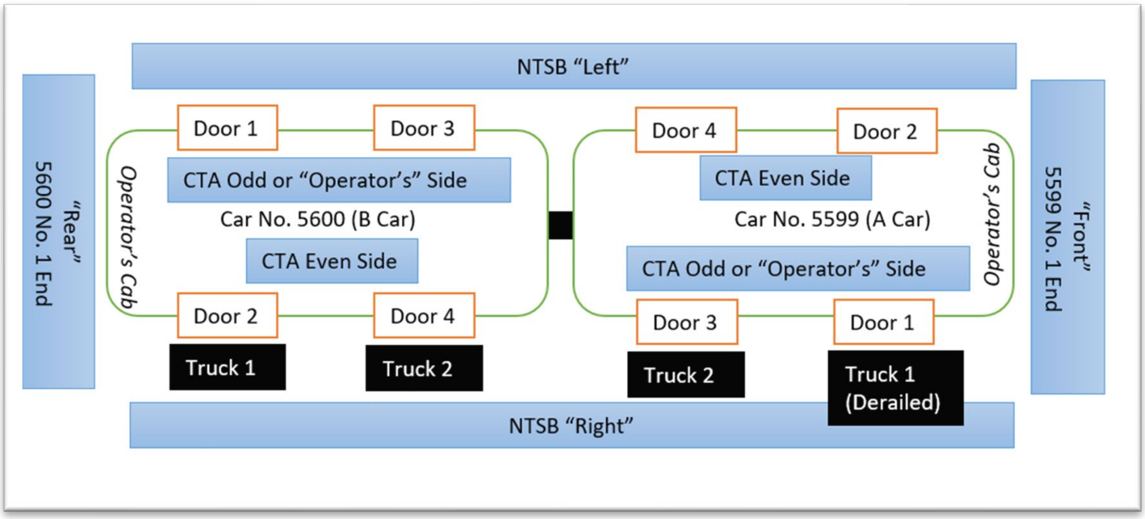

Figure 1. Factual report orientation diagram. Direction of travel was from left to right.

2.0 Struck Machine

Rail Borne Snow Removal Vehicle S-500 is a specialized piece of maintenance equipment purchased by CTA from Mitsubishi International Corporation and built by Niigata Engineering Company Limited of Japan in 1981. The diesel driven; airbrake equipped vehicle has two bi-directional cabs that permit the machine to be operated in the forward direction from either end. End No. 1 is designated as the end that is facing the plow assembly and End No. 2 faces the brush assembly. The S-500 weighs 89,500 lbs. At the time of the accident, the snow removal vehicle was stopped on the southbound track with End No. 1 on the southernmost end of the track. The accident train collided with the brush assembly on End No. 2.

E DETAILS OF THE INVESTIGATION

1.0 Mechanical Examination

The Mechanical Working group convened at the CTA Maintenance Facility in Skokie, Illinois the week of December 18, 2023. The group conducted mechanical inspections of the striking train, struck train, and dynamic brake exercises using an exemplar trainset (5525/5526).

1.1 Mechanical Condition - Car No. 5599

- No. 1 End Cap was destroyed with the exception of separated portions of the top right and bottom left. The destination sign had impact damage consistent with impact from the S-500 coupler. The end cap in front of the left collision post was intact, with yellow witness marks beginning near the bottom of the left corner post 5' ATOR in an arc pattern. At the collision post, a 14" yellow scraping mark was noted. The bottom right end cap portion was recovered with similar yellow witness marks. All windows were missing but recovered with collision damage.
- All front grab handles were destroyed.
- The No.1 End Door was destroyed in the collision.
- All wheels showed flat spots ranging from ½" to 2" in length, consistent with wheel slide and slip/slide system activation.
- The number one gear unit had an approximate 1"x1"x1" impact mark at the lower right corner and was missing one bolt. The gear unit was leaking fluid, this evidence was consistent with derailment damage.
- The anticlimber was intact and not deformed, however the carbody was bent in that area causing the Anticlimber to be raised upward about 12". Witness marks 5" each side of center matched impact marks on the front brush (snow broom) gearbox of the S-500.
- The left collision post was deformed up and inward. Significant impact deformation/crush approximately 65-inches above the floor.
- The right collision post was retained in the lower floor structure, the welds did not fail. The top plate structure of the end sill was torn. Similar deformation/crush damage as the other collision post. The center of the deformation was about 40 inches above the floor. The safety chain and end cap were still attached.
- The right corner post was deformed, the center of impact was about 15 inches above the top plate. The connection to the bottom plate was intact. The top plate was torn.
- The left corner post was deformed in the same manner. The center of deformation was about 20 inches above the top plate. The top plate was torn at the post.
- The Anti-telescoping (AT) plate was separated into two parts, on the non-operator's side the AT plate was 36" long. It was also separated from both corner posts at their attachment locations.

- The corners of both side sills were crushed and torn. The deformation was limited to the end sill portion,
- The No. 1 end coupler head shear bolts were not damaged.
- The No. 2 end shear bolts were all broken.
- The four shear bolts are designed to work together to absorb 90,000 lbs. of force before failing. The evidence is consistent with the front coupler not striking the S-500 due to the raised S-500 coupler.
- The condition of the No. 2 end shear bolt break and witness marks indicated the Anticlimbers of 5599 and 5600 engaged.

1.2 Mechanical Condition - Car No. 5600

- No. 2 end Anti climber witness marks and plastic deformation of the end sill are consistent with collision.
- All wheels had flat spots ranging from 1/2” to 2” in length, consistent with wheel slide.

1.3 Mechanical Condition - S-500 Snow Machine

- At the time of the collision, the No. 2 End Coupler was raised via hydraulic pistons. Post-accident, the brush housing was noted to be rotated about 15-degrees, resulting in the following measurements to be greater than the initial impact height. The top of the coupler was located about 122-inches above the top of rail, and offset about 18-inches to the left (direction of travel).
- The top of the arched coupler beam was about 105-inches above the top of rail.
- Behind the coupler beam, the brush housing was collapsed inward approximately 8”.
- The brush housing has gouges and witness marks that are consistent with the Series 5000 anti-climber impacts.
- The coupler beam is attached to structural elements surrounding the brush. These are approximately ½” steel plates. The plates are rotated clockwise (from the right side of the equipment) approximately 10-15 degrees.
- The brush housing and brush are connected to the front cab of the S-500 with 4” connecting rods, each approximately 63” long and secured with pins.

- The upper connecting rods are deformed, with a visible upside down U shape, and paint deformation, approximately 12” from the cab. The length of the deformation is approximately 10”.
- The No. 2 End Cab Wall is deformed inward approximately 10” across it’s full width.
- Structural elements of the S-500 are protruding from the front cab wall in the proximity of the cab floor.
- Window glazing and gaskets from the front of car number 5599 are resting on top of the brush, behind the coupler beam. The glazing is shattered.
- Glazing from the S-500 cab is broken and resting on top of the brush
- The drive shaft for the brush is disconnected, but not broken, at two locations.
- The gasket for the S-500 cab glazing is approximately 5% retained, with the remainder hanging loose.
- The center post between the cab windows is broken at the bottom connection.
- Inside the cab, the floor directly in front of the right side seat is raised/deformed approximately 4” upward
- There was no damage noted to the No. 1 End of S-500, including the No. 1 End Cab.

1.4 Mechanical Condition at the Collision Interface

- The train and snow machine were placed together on a shop track to better investigate the collision interface.
- It was noted that the 5599 secondary suspension includes a hydraulic leveling system which was depressurized during the inspection, resulting in the car height being lower than at the time of the accident (about 3 inches)
- It was noted that the S-500 brush housing was rotated about 15-degrees, which resulted in the coupler beam resting higher than its normal pre-accident position. Witness marks found on the 5599 are consistent with this rotation.
- The coupler of the S-500 was rotated fully to the left of the machine.

- Paint transfer from the S-500 to the end cap of the 5599 generally matched across the full width of the vehicles, most notably from a point 5' above the top of rail at the lower portion of the corner posts, in an upward arc that matched the S-500 coupler carrier beam. However, the upper portions of the paint transfer did not match precisely. The group attributes this difference to the rotation of the S-500 brush housing due to collision damage, the height of the 5599 secondary suspension at the time of the inspection, and the crush damage to the structure of 5599.
- The group noted that the anti-climber of 5599 engaged with the brush housing, and there was no evidence of telescoping behavior at the collision interface.
- The group discussed the following possible evidence that the 5599 experienced vertical lift during the collision.
- The end sill was buckled up and back.
- Video evidence suggests that unrestrained passengers traveled both forward and downward (relatively, into the floor) during the collision.
- The number one truck derailed suggesting that, at a minimum, that the vehicle had enough vertical displacement to raise the wheel flanges over the rail head.
- There was no evidence of contact between any truck component and the bottom of the car structure.

Static Testing

- The track brake system was tested on the trainset. Car 5600 was used as the operating cab. Car 5600 track brakes functioned normally. Car 5599 track brake operator controls and track brake solid state contactors were damaged in the collision. The track brakes of 5599 functioned normally when an external power source was applied to the track brakes.
- The disc brake system was tested. All brake calipers were visually observed to function normally.
- A load cell (force gauge) was installed on each brake caliper. The team notes that the load cell was made for a different caliper, and is rarely used. CTA bench tested the load cell prior to use in these tests and found the device to be accurate.
- The nominal output force of a new 5000-series caliper is about 700 to 800 pounds.
    - The mechanical team notes that the wheels slid during the accident indicating that sufficient brake pressure was available during the accident sequence.

- The mechanical team requested that 4 brake calipers from 5599 be removed for bench testing.
- The results of the on-train caliper force measurements as well as the bench test results are included in the table below.
- The calipers tested on the bench were noted to have sticking slack adjusters.
- Car 5599 has accrued 522,529 miles on original truck number 1, and 173,113 miles on replaced truck number 2. CTA notes that the number 2 replacement truck was likely a capital spare truck since the calipers were not rebuilt.

Car	Caliper Position	Caliper S/N	Measured Force (1st time) (psi)	Measured Force (2nd time) (psi)	Bench Test Force	Rebuilt Date	Note
5599	**1**	**471415**	**321**	**728**	**521**		**Original**
	2	**471412**	**455**	**480**	**686**		**Original**
	3	**261544**	**841**	**814**	**636**		**Truck replaced in 2020**
	4	**261546**	**625**	**475**	**647**		**Truck Replaced in 2020**
5600	**1**	**131214**	**714**	**N/A**	**N/A**	**1/3/2023**	**Original**
	2	**471409**	**652**	**N/A**	**N/A**		**Original**
	3	**391457**	**578**	**N/A**	**N/A**	**4/17/2019**	**Original**
	4	**431491**	**345**	**N/A**	**N/A**		**Original**

1.5 Post-Accident Dynamic Testing

1.5.1 Overview

Several days of post-accident dynamic testing were conducted using exemplar 5000-series trainsets. The table below summarizes the different testing days, and the sections below provide additional details.

Date	Test Summary
November 20, 2023 (CTA Only)	Five test runs conducted. The weather was 45-degrees with light rain conditions. One test aborted due to non-favorable operator inputs. Two runs from 55 mph with full-service brake. One test conducted at 35 mph to verify proposed post-accident safety action speed reductions. All 'validated' tests stopped short of the entrance to the 9T signal (beyond which was occupied by the S-500 on the day of the accident).
November 22, 2023 (CTA Only)	Seven test runs conducted. A shunt was applied at the S-500 location to simulate its presence. The weather was 45-degrees and partly cloudy. Five test runs were conducted at 55 mph, all of which exceeded the 9T track circuit distance. Of those, only one stopped short of the simulated S-500 position, implying four runs would have resulted in a similar collision. Two test runs were conducted from 35 mph. Both runs stopped short of the 9T track circuit.
November 27, 2023 (CTA Only)	Thirteen test runs were conducted. Prior to testing, the rails were cleaned using a power washer. A shunt was applied at the S-500 location to simulate its presence. The weather was 25-degrees and clear. Two test runs at 35 mph stopped short of the 9T track circuit. Of the 55 mph runs, seven exceeded the 9T track circuit and four resulted in a simulated collision. Four 55 mph tests stopped short of the 9T track circuit.
December 19, 2023 (CTA, Alstom, and NTSB)	Fourteen test runs. All tests were conducted from 55 mph. Weather was 24-degrees F and clear. Additional details below.

1.5.2 Post-Accident Dynamic Testing

On December 19, 2023 fourteen test runs were conducted. The first 7 tests were conducted to estimate the available rail adhesion. The eighth test was a repeat of the first two. The comparison between the two helped estimate the amount of "rail cleaning" which had occurred as a result of the testing. It is noted that the final two tests stopped about 500-feet sooner than the first tests, indicating that significant rail cleaning had occurred.

The mechanical group notes that it is extremely difficult for an operator to accurately apply a specific range of full-service brake applications with a 5000-series master controller. To assist the operator, a graduated marker was placed next to the master controller, despite this, the percent-of-brake application is only an estimate.

The rail adhesion was then modified with water sprayers for the remaining tests. Tests 9-12 were also recreations of the accident scenario. The final two tests were conducted using "full emergency" at the entrance to the 26T track circuit. The first full emergency was with the slip/slide track brake feature "off", and the last one with the feature "on". Results of the testing are summarized in the table below.

Run No.	S 500 Shunt	Max Speed (mph)	Distance to full stop measured from entrance to 9T (feet)[5]	Total braking distance	Simulated Collision	Wet Track		Description of test conditions
1		55	172	2070	N			Full-service brake at 26T
2		55	-119	1779	N			Full-service brake at 26T
3		55	-479	1419	N			ATC Bypass ~75% Full Service
4		55	18	1916	N			ATC Bypass ~75% Full Service
5		55	122	2020	N			ATC Bypass ~75% Full Service
6		55	-583	1315	N			ATC Bypass ~50% Full Service
7		55	-705	1193	N			ATC Bypass ~50% Full Service
8		55	320	2218	Y			Full-service brake at 26T
9	Y	55	396	2294	Y	Y		Incident recreation
10	Y	55	-461	1437	N	Y		Incident recreation
11	Y	55	-169	1729	N	Y		Incident recreation
12	Y	55	-263	1635	N	Y		Incident recreation
13		55	-620	1278	N			Emergency w/ slip-slide track brake feature "off"
14		55	-650	1248	N			Emergency w/ slip-slide track brake feature on

The team discussed reasons that a 50% full-service brake resulted in a shorter stopping distance than a 75% or 100% full-service brake. It was noted that the 50% full-service brake did not result in wheel slide, whereas 75% and 100% resulted in sliding wheels. Using this information, the team concluded that the rail adhesion was sufficient for 50% braking, but not 75% or more. By better utilizing the available adhesion, the train was able to stop in a shorter distance.

The team also discussed reasons why the 13th and 14th tests resulted in short stopping distances and little difference between the two tests. It was determined that the frequency of tests and heavy braking 'cleaned' the rail, such that rail adhesion had improved by the end of the test regimen, and wheel slide was no longer a factor.

[5] A positive number indicates the train passed the 9T circuit. A negative number means the train stopped prior to the 9T circuit. A positive number in excess of 250 indicates a "simulated collision", as that was the position of the S-500 on November 16th.

The table below summarizes information from the event recorder downloads and videos recorded during testing.

Run No.	Description and Expectations of Test	Notes from Event Recorder	Notes from Video
1	"Available adhesion level test" Full-service brake at 26T. Sliding wheels expected due to requesting a full-service brake rate (2.8mphps).	• Dynamic brakes apply at about 10:28:10 • Wheel slide detected about 1-second later • Dynamic brakes modulate • As the speed is reduced below 5mph, the friction brakes come on and the dynamic brakes fade out •	• 0:37 – Movement begins • 1:45 – Passed cone for 26T Bond • Wheel slide protection system evident until: • 2:06 – Wheels lock, friction brakes likely applied at this point • 2:28 – full stop
2	"Available adhesion level test" Full-service brake at 26T Sliding wheels expected due to requesting a full-service brake rate (2.8mphps).	• Dynamic brakes apply at about 10:41:10 • Wheel slide detected about 1-second later • As speed is sensed below 5mph, friction brakes apply and dynamic fades out. • A second wheel slide is noted at 10:42:20 • The friction brake reduced pressure until wheel slide is no longer noted.	• 0:31 – Movement begins • 1:40 – passed 26T Bond • Wheel slide protection system evident until: • 1:57 – Wheels lock. • 2:01 – Some wheel rotation until the end • 2:17 – Full stop •
3	"Available adhesion level test" ATC Bypass ~75% Full Service Sliding wheels likely due to requesting a full-service brake rate (~75% of 2.8mphps).	• Dynamic brakes apply at about 10:53:56 • Dynamic brake pattern is much different under slide protection that previous runs. B does not sense a slide until 10:54:16 whereas A sense a s slide immediately, but modulates differently than before. A stops slide sensing before be begins sliding • Full friction at about 10:54:23	• 0:29 - Movement begins • 1:39 – Passed 26T Bond • Wheel slide protection not as evident until about 2:00 • 2:20 – Full stop
4	"Available adhesion level test" ATC Bypass ~75% Full Service Sliding wheels likely due to requesting a full-service brake rate (~75% of 2.8mphps).	• Dynamic brakes apply at about 11:04:59 • Both trucks sense slide almost immediately. The pattern is similar to the first runs • Friction and dynamic are blended at the end more clearly.	• 0:38 – Begin movement • 1:46 – Passed 26T Bond • Slide protection isn't clearly evident until about 1:58 • Wheels never stop rotating until full stop • 2:23 - Full stop

5	"Available adhesion level test" ATC Bypass ~75% Full Service Sliding wheels likely due to requesting a full-service brake rate (~75% of 2.8mphps).	• Dynamic brakes apply at 11:17:04 • immediately. The pattern is similar to the first runs •	• 0:27 run begins • 1:37 – Passed 26T Bond • Slide protection is evident, but wheels never stop turning until full stop • 2:14 – full stop
6	"Available adhesion level test" ATC Bypass ~50% Full Service Sliding wheels possible due to requesting a full-service brake rate (~50% of 2.8mphps). (no wheel slide encountered)	• Dynamic brakes apply at 11:24:11 • No slip slide • Friction brakes blend in at about 11:24:47	• 0:30 movement begins • 1:38 – passed 26T Bond • 2:13 – Full stop
7	"Available adhesion level test" ATC Bypass ~50% Full Service Sliding wheels possible due to requesting a full-service brake rate (~50% of 2.8mphps). (no wheel slide encountered)	• Dynamic brakes apply at 11:33:54 • Truck B wheel slide protection three separate times starting around 11:33:54. Dynamic brakes modulate for each.	• 0:41 Movement begins • 1:49 – passed 26T Bond • 2:21 – full stop. Wheels never stopped spinning
8	Full-service brake at 26T	• Dynamic Brakes apply at about 11:41:15 • Slide protection immediately engages • When speed gets below 5, the friction brakes come on, and do not release again, event though the speed shows that it increased from near zero to 40 mph prior to full stop.	• 1:16 – Movement begins • 2:25 – passed 26T bond • Slide protection evident • 2:43 – Wheels nearly stop, but pick up speed quickly after that • 3:09 = full stop
9	Incident recreation	• Dynamic brakes apply at about 12:34:56 • Immediate slide protection system activation • Similar to run 8, when dynamics blend out, friction brakes return and the wheels pick up speed. • Two additional slide protection events.	• 1:10 – movement begins • 2:21 – Passed 26 T bond • Slide protection system evident • 2:36 – Wheels nearly stop, then pick up speed. • 2:51 – Wheel slide • 2:26 – Track brake activates? •
10	Incident recreation	All tests similar to above.	
11	Incident recreation		
12	Incident recreation		
13	Emergency w/ slip-slide track brake feature "off"	By this time rail adhesion had increased to the point we were no longer getting wheel slides.	
14	Emergency w/ slip-slide track brake feature on	By this time rail adhesion had increased to the point we were no longer getting wheel slides. Track brake activation was not evident in the video.	

1.5.3 Summary of Testing

On the day of testing the Mechanical Team notes that there was sufficient rail adhesion present for braking without activating the slide protection system so long as only 50% of full-service was called for, or about 1.4 mphps. There was not sufficient rail adhesion for 75%-100% (2.1 – 2.8 mphps) without activating the slide protection system. The team notes that when the train senses speeds below 3 mph, the friction brakes blend in and do not release even if better adhesion is obtained and the wheels begin rotating again.

2.0 Pre-revenue service Brake Rates/ Qualification Testing (2009)

2.1 Qualification Testing – Deceleration Rates

Deceleration (braking) performance qualification tests for the 5000-series cars were conducted in November 2009, with final reports completed in December 2009. The reports demonstrate that the 5000-series vehicles met the performance and jerk rate requirements provided in the CTA Technical Specifications for the cars. The tests were conducted at a load of AW0 + 1,500 lbs. The first test was conducted in Plattsburgh, New York at speeds up to 30 mph. The second test was conducted on the CTA Red Line between Howard and Addison stations at speeds of 55 mph up to 70 mph.

Compliance was verified against CTA Technical Specifications (design specifications). Select relevant specifications are described in the table below.

Technical Specification	Requirement
Section 10.02.B	The propulsion system shall not adjust performance based on passenger loads.[6]
Section 10.02.B.4	Minimum Service Brake Rate is 0.5 mphps with electric braking, and between 0.5-1.0 mphps with friction braking
	Maximum Service Brake rate is 2.8 +/- 0.1 mphps from maximum speed. This is a blended brake with electric brakes fading out and supplemented with friction brakes as the train comes to a full stop.

[6] In other words, the deceleration rate should be the same regardless of passenger load.

	Emergency Brake rate is 2.8 (+/- 0.1) mphps *plus* 2.5 (+/- 0.1) mphps *plus* track brake effort using electric, friction, and track brakes.
Section 10.07.C.2	Normal service stops are made with the electric brake which maintains the brake rate to approximately 3 mph. As the electric brake fades, the friction brake is smoothly blended in to complete the stop and hold the train.

The tests were conducted with Car Nos. 5011 and 5012 which weighed 55,561 and 55,551 respectively. All tests were conducted on tangent and level sections of track with dry rails.

Brake rates were calculated by taking the average deceleration rate read from an accelerometer plot on the constant portion of the braking curve. For the testing conducted at CTA, 5 runs at 55 mph were conducted, and 7 runs at 70 mph were conducted. The runs included blended and friction only maximum braking and emergency braking.

The results obtained during the deceleration tests complied with the requirements of the CTA technical specifications for the 5000-series cars. Specifically, brake rates for emergency brake applications all exceeded 5.1 mphps, and exceeded 7 mphps on one occasion.

2.2 Qualification Testing – Spin/Slide System

Qualification testing of the spin/slide system was conducted in May 2007 in Plattsburgh, New York. The objective of the test was to demonstrate compliance with CTA Technical Specifications. The tests were conducted at speeds up to 30 mph with Car Nos. 5001/5002 loaded at AW0 + 1,500 lbs.

The original CTA Specification called for track brake application upon wheel slide detection, section 1.1.2 of the qualification test report states, "it has been agreed after the tests, that the runs without the automatic track brake application would serve as the qualification test runs".

The brake slide protection was demonstrated with one run where dynamic, friction, and track brakes were applied during the run from 30 mph to 0 mph.

Compliance was verified against Technical Specifications. Select relevant specifications are described in the table below.

Technical Specification	Requirement
Section 10.03.J.3	Tractive and electric braking effort during wheel spin/slide correction shall be modulated on a per inverter basis. Slide protection for friction brakes shall be on a per-car basis.
Section 10.03.J.6	At a coefficient of adhesion of 0.05 (5%) or greater, the efficiency of the wheel slip system shall be at least 80-percent in acceleration and braking over the speed range between the maximum speed and 3 mph.
	Wheel slide efficiency is defined as the ratio of the actual braking rate to the theoretical braking rate from brake entry speed to a lower speed.
Section 10.03.J.8	Upon detection of an incipient slide, the propulsion system shall quickly, without jerk limit, reduce the braking effort and apply the track brakes.[7] The subsequent increase in braking effort will prevent damage to wheels and minimize stopping distance.
	The wheel slide function is user-selectable between "Continuous" and "Time-Out".[8]
Section 10.03.J.9	Activation of the wheel spin-slide function during emergency brake applications shall be user selectable and shall initially be set to "on".
Section 10.07.A.1	Track brakes shall also be energized when the master controller is in the "Emergency Brake" position. Track brakes throughout the train are energized, except when the slide system applies them on a per-car basis.

Prior to delivery to the test facility, Car Nos. 5001 and 5002 weighed 55,802 lbs. and 55,800 lbs., respectively.

For the test reports, wheel slide efficiency was calculated using the following formula:

$$Wheel\ Slide\ Efficiency = \frac{Achieved\ brake\ rate}{Theoretical\ Acceleration\ rate}$$

Slippery conditions were simulated with a mixture of biodegradable liquid soap and water applied in front of the axles before and during the test runs.

[7] As discussed elsewhere in this report, the requirement to apply the track brake was later removed.
[8] At the time of the accident, the train slip slide system was in "Continuous" mode.

2.2.1 Discussion on Track Brake Application during slide system qualification

Full-service brake slide test runs were carried out with and without track brake application. It was observed that a short application of the track brake during a slide correction introduced high variations in the brake rate and it was preferable to maintain track brake for the duration of a slide correction. Section 6.2.2 states,

> *"However after comparison of the results obtained during the qualification test runs it was judged that the "continuous" track brake application during slide corrections would provide a very high braking rate which could cause discomfort to the passengers. It was then decided to disable automatic track brake application during slide corrections (ref: letter BTCTA-1282) and leave to the operator to judge whether he needed a higher braking rate by applying manually the track brake during slide correction."*

During a conference call held on May 22, 2009, it was decided to use the slide runs without track brake to generate the report.

2.2.2 Discussion on Adhesion during slide system qualification

According to the 2009 qualification test report, track adhesion level varies with weather, dust, rail type, and general condition of rail surfaces. It varies over time and it is impossible to maintain a constant adhesion level. In order to carry out the tests, a water-soap solution was placed on the rail surface before and during the runs.

Furthermore, according to the report, under dry rail conditions, when the brakes are applied, the deceleration rate increases up to a predetermined level as dictated by the capability of the equipment. Under slippery rail conditions, the deceleration increases only up to the maximum adhesion achievable on that section of track. An increase of the braking effort beyond that adhesion level will cause the wheels to slide and wheel speed will 'break away' from the real train speed. Under severe slide conditions, the wheel rotation will 'lock'. In order to prevent damage to the wheel that is caused by sliding wheels, the slide control releases the braking effort in attempt to allow the wheels to regain adhesion on the rail. When the wheel speed stops decreasing and starts increasing again, the slide protection system slowly reapplies the braking effort to the wheels.

During the full-service dynamic and friction braking runs, slide activity was observed throughout the entire speed range. Slide conditions corresponded to adhesion levels between 5% and 10% adhesion, which was the target for the demonstration.

The emergency slide protection braking run was performed starting at 30 mph. Some slide activity was observed at the beginning of the braking and rapidly decreased throughout the braking period. The automatic control of the track brake in emergency quickly dominated the braking deceleration, quickly exceed 5 mphps and reaching 7 mphps under slippery conditions.

The report concluded that the CTA-5000-Series spin/slide protection system met the requirements of the specifications. The efficiency of the system was above 80% as required. The quantity of soap and water used was sufficient to result in low adhesion limits.

For the deceleration tests, the distances to stop were also recorded. Without track brake, the train stopped from 30 mph 599 feet to 635 feet. With the track brake, the train stopped in 99 feet.

2.3 Qualification Testing Summary

The qualification reports indicate that the vehicle was tested against the design specifications, and the vehicles performed as specified. However, the qualification test reports do not indicate that testing was performed under any ‘worst-case’ scenarios as may be encountered at CTA (such as maximum grades, environmental conditions, or signal spacing).

3.0 Discussion on Adhesion Demand

Adhesion between the wheel and rail is normally expressed as a coefficient of friction (symbol μ). The UK Rail Accident Investigation Branch provided the following explination of this coefficient in Report 25 (Part 1)/2006 in January 2007 (emphasis added).[9]

> *The lower the value of μ, the lower the adhesion between wheel and rail. Typical values for μ for dry rail would be at least 0.20 (20%). In wet weather, this can fall to 0.10 (10%). Under severe low adhesion conditions, the value of μ can drop below 0.03 (3%). As trains rely on the coefficient of friction between wheel and rail to stop, the level of adhesion available is critical to the rate at which the train decelerate. Many modern trains have four or five fixed braking rates available to the driver (operator), the lowest of which will normally achieve a deceleration rate of 0.3 m/s^2 (0.67 mphps) and the highest a rate of at least 1.2 m/s^2 (2.68 mphps). A braking rate of 0.3 m/s^2 can only be achieved if the value of μ is at least 0.03 (3%).* ***The value of μ would need to be at least 0.12 (12%) to sustain an emergency braking rate of 1.2 m/s^2.***

In the report referenced above, rail adhesion was found to be 3% or less due to leafy debris on the track, causing a signal overrun.

In the United States, APTA released a "Baltimore LRV Case Study" in May 2017.[10] This report discusses the inability of a particular LRV to achieve a required 1.5 mphps brake rate when adhesion rates were below 7% due to mist, dew, and leafy conditions. As a result of the study, track brakes were deployed during low-adhesion conditions and a rail cleaning program was initiated.

Also in the APTA report, a table was derived from information presented by Harry G. P. Burt and E. Saumweber at the IEE/ASME Joint Railroad Conference, 1985. The table is presented below as a reference for industry knowledge regarding adhesion levels and available brake rates for various railhead conditions. Note that wet leaves present lower adhesion levels (less than half) than wet rail and that average deceleration is reduced as speed is increased.

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[9] https://assets.publishing.service.gov.uk/media/5a7598f3e5274a43682987ee/070108_R252006_Part_1_Esher.pdf
[10] https://www.apta.com/wp-content/uploads/RC17-Maryland-DOT.pdf

Speed (mph)	Wet Leaves		Damp Rail (Lower Limit)		Dry Rail (Lower Limit)		Dry Rail (Upper Limit)	
	% Adhesion	AW0 Decel. (mphps)	% Adhesion	AW0 Decel. (mphps)	% Adhesion	AW0 Decel. (mphps)	% Adhesion	AW0 Decel. (mphps)
10	3.5	0.77	8.0	1.76	11.0	2.41	21.5	4.72
30	3.0	0.66	7.0	1.54	9.5	2.09	18.0	3.95
50	2.5	0.55	6.0	1.32	9.0	1.98	15.5	3.40

Note: The table is derived from information presented by Harry G. P. Burt and E. Saumweber at the IEEE/ASME Joint Railroad Conference, 1985. The AW0 Deceleration figures assume an evenly distributed load and that all wheels in the train (or vehicle) are doing equal amounts of work

As seen above, rail adhesion can be thought of in terms of "adhesion required" to achieve a certain brake rate. To derive the approximate adhesion required, the brake rate is divided by the normal force of gravity as shown below for a brake rate of 2.8 mphps.

$$adhesion\ required = \frac{brake\ rate\ (mphps)}{gravity\ (mphps)} \times 100 = \frac{2.8\ mphps}{21.9\ mphps} \times 100 \approx 13\%$$

Similarly, if the brake rate is known, the "available adhesion" can be estimated.

$$adhesion\ required = \frac{brake\ rate\ (mphps)}{gravity\ (mphps)} \times 100 = \frac{1.08\ mphps}{21.9\ mphps} \times 100 \approx 4.9\%$$

4.0 Review of Brake System

Relevant portions of the 5000-Series maintenance manuals were reviewed to better understand the brake system.

4.1 Traction Motors

During normal service braking conditions, traction motors provide electric braking for all speeds above 3 mph. The traction motors perform as generators using the energy of the rotating wheels converted into electrical current to slow the car. The electrical power produced can be returned to the third rail or directed to brake grid resistors located under the car where the energy is dissipated as heat.

In the final phase of braking, electric braking fades out and friction braking begins to take over progressively and proportionally. This is known as blended service braking and ensure a smooth and even deceleration rate. Blended braking begins at 5 mph and finishes at 3 mph when fade out of the electrical motors is complete. At 3 mph, only friction braking remains to decelerate the car.

4.2 Friction Braking

The friction brake is a floating-type, spring-applied, and hydraulically released disc brake caliper unit. The disc brake calipers are used during both service braking and emergency braking. And as a part of blended braking as described above.

Under normal conditions, the disc brake caliper is held in the release (off) mode with hydraulic pressure acting on a piston that compresses the disc springs. When a brake application is called for, hydraulic pressure acting on the piston is reduced and spring force is transferred to the brake head through a slack adjusting nut.

4.3 Wheel Spin and Slide Protection

A description of the spin and slide protection system is found in section 6.3.2.1.7. The system detects wheel spin (in power mode) and wheel slide (in brake mode) by constantly monitoring the car speed with acceleration and deceleration rates of the truck axles. When a slide is detected, tractive effort is systematically modulated to correct the slide. When a slide is detected during friction braking, the friction brake proportional valve current is used to modulate friction brake effort until the slide is corrected. As described earlier in this report, when a slide is detected, the track brakes are not enabled (as an operation choice by CTA). The maintenance manual also describes the slide time-out feature, which was not enabled on CTA's 5000-series.

5.0 Carbody Structural Reports

The CTA 5000-Series Carbody Crash Analysis report was submitted to CTA on September 26, 2007 by Bombardier. The report confirms compliance with CTA Technical Specification Section 3.01.D. The report describes the crushing behavior of the carbody in a collision between two trainsets, each with 2 cars, and loaded to AW0 with a relative velocity of 10 mph. The energy absorbed in this scenario is similar to a single trainset striking a ridged wall at 5 mph. The report concludes that a coupler-to-coupler collision will deform the carbody at the extreme ends first, which complies with CTA specifications. The mechanical group notes that the initial impact of the accident train with the S-500 was not a like-train-collision-scenario, and the evidence is consistent with a higher-speed impact much higher than the coupler occurring first.

Submitted by:

John Manutes
Railroad Accident Investigator

APPENDIX A – LIRR AND OTHER RR LEAF PROGRAMS

During the course of the investigation, the mechanical team noted several railroads that maintain "rail cleaning" or "leaf programs" to protect against the negatives effects on rail adhesion due to organic or other debris on the rail head.

MTA LIRR Expands Leaf-Fighting Capabilities with Lasers, Truers, & Power Washers, MTA LIRR YouTube, https://www.youtube.com/watch?v=zL21bWhNsv0&pp=ygUObXRhIGxlYWYgdHJhaW4%3D

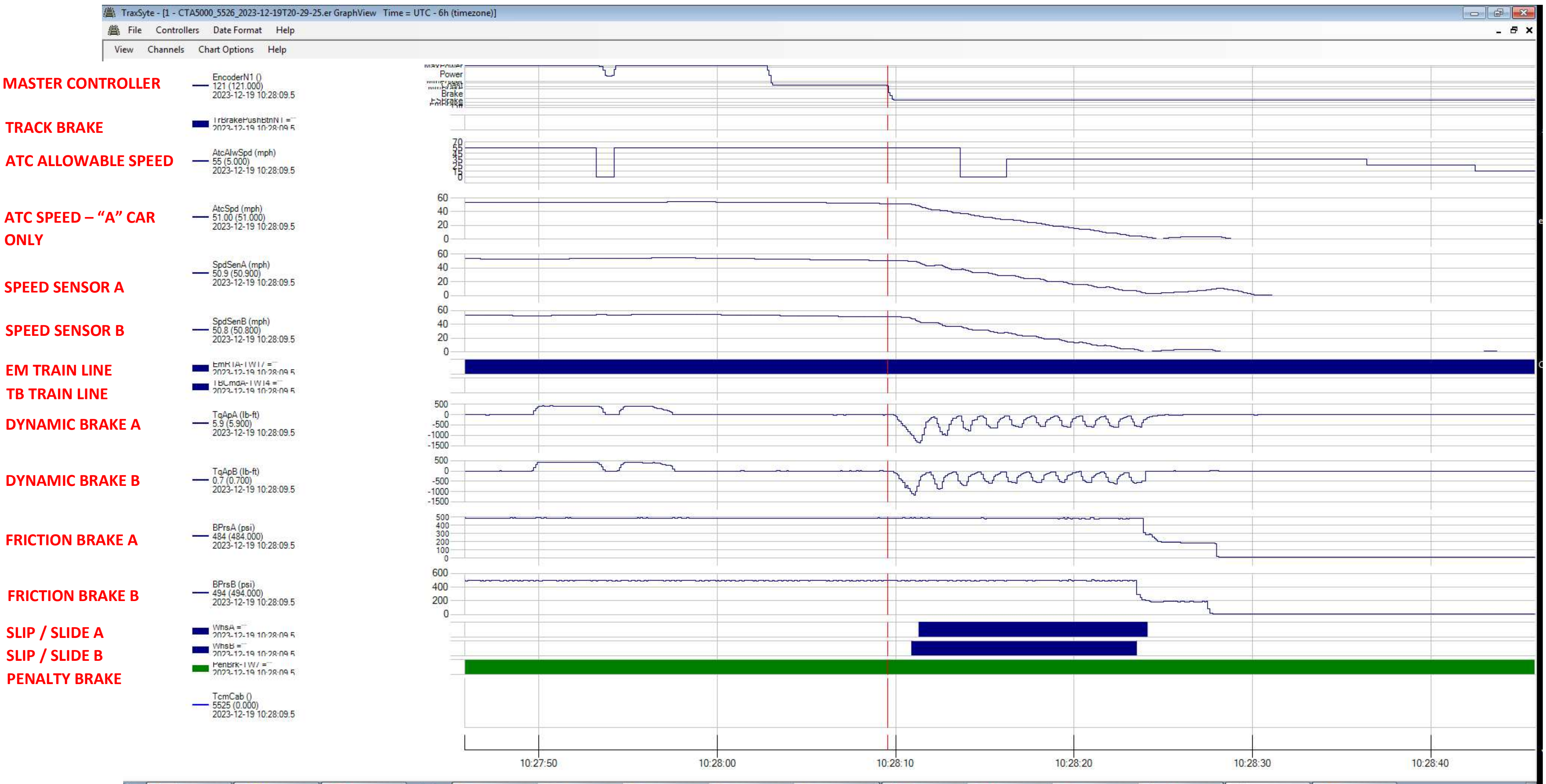
Metro-North Laser Train wins APTA Rail Safety Gold Award, MTA Today YouTube, https://www.youtube.com/watch?v=LCeT93EYAEs&pp=ygUObXRhIGxlYWYgdHJhaW4%3D

Laser and plasma jets zapping leaves on the line, Network Rail (UK) YouTube, https://www.youtube.com/watch?v=FTB0O_QmOWI&pp=ygUKbGVhZiB0cmFpbg%3D%3D

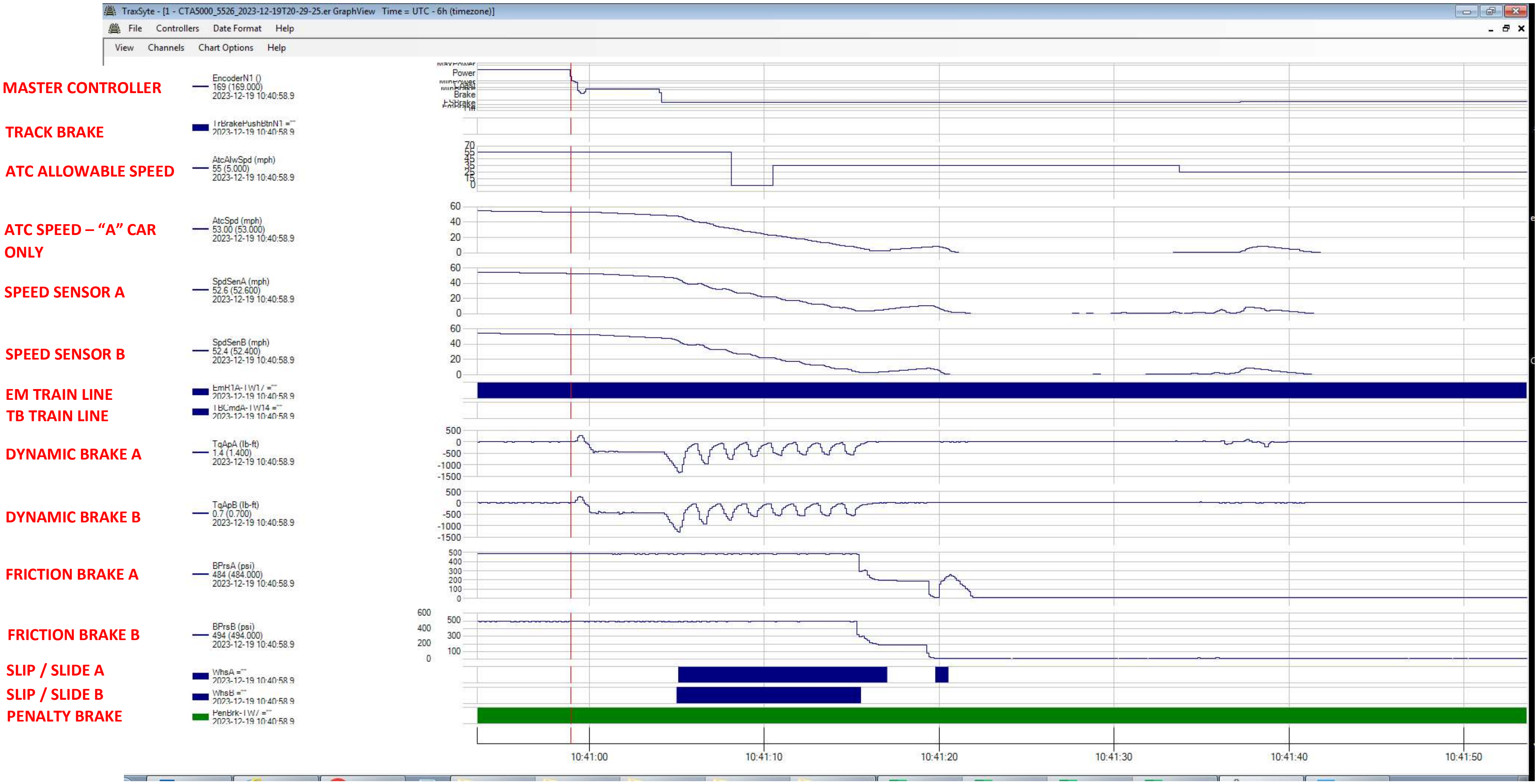
Leaves on the Line, Ingenia (UK), https://www.ingenia.org.uk/articles/leaves-on-the-line/

APPENDIX B – NTSB DYNAMIC TEST RECORDS

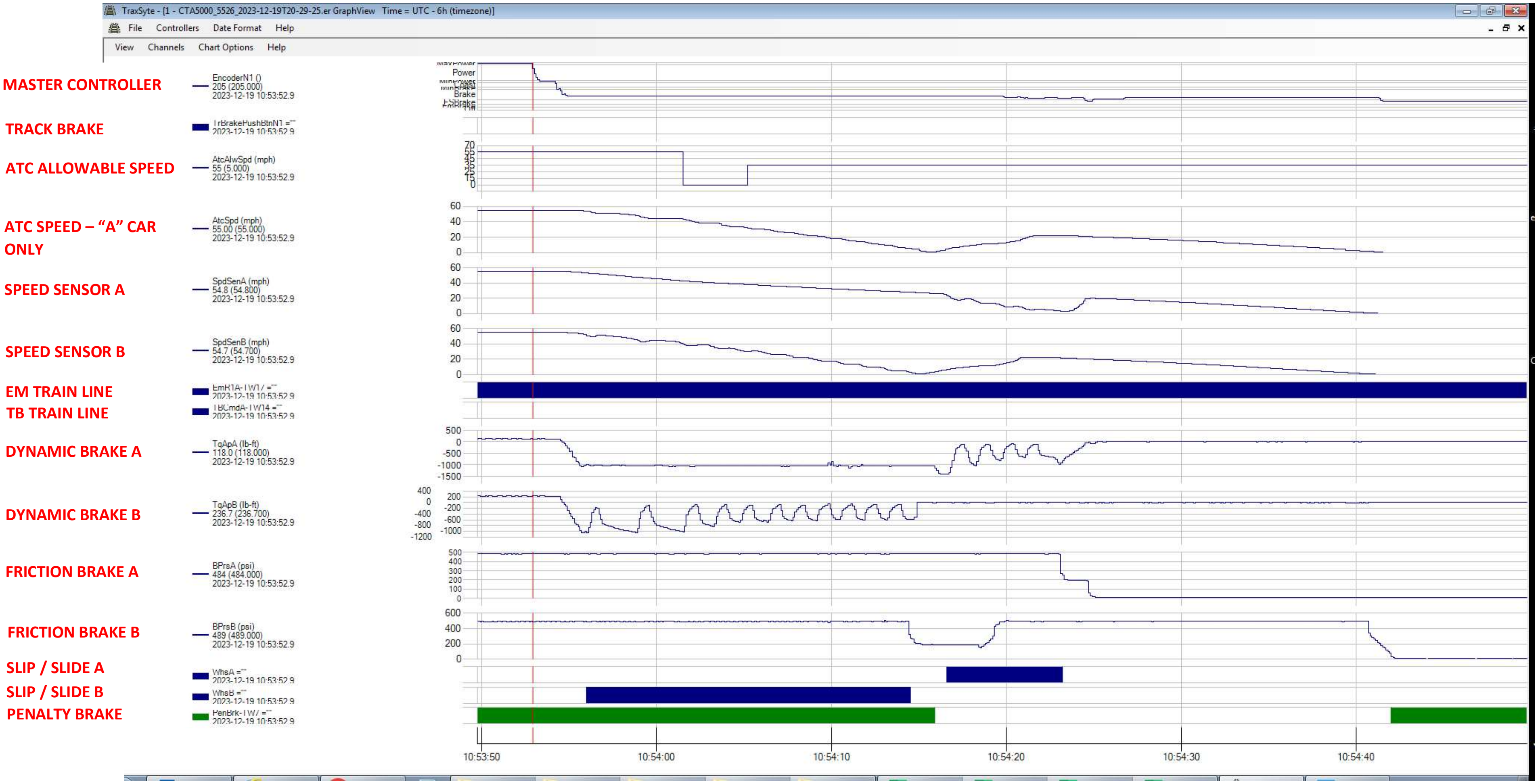
Test Run #1 ERU Event Log – Operator acts normally; full service brake at 26T bond



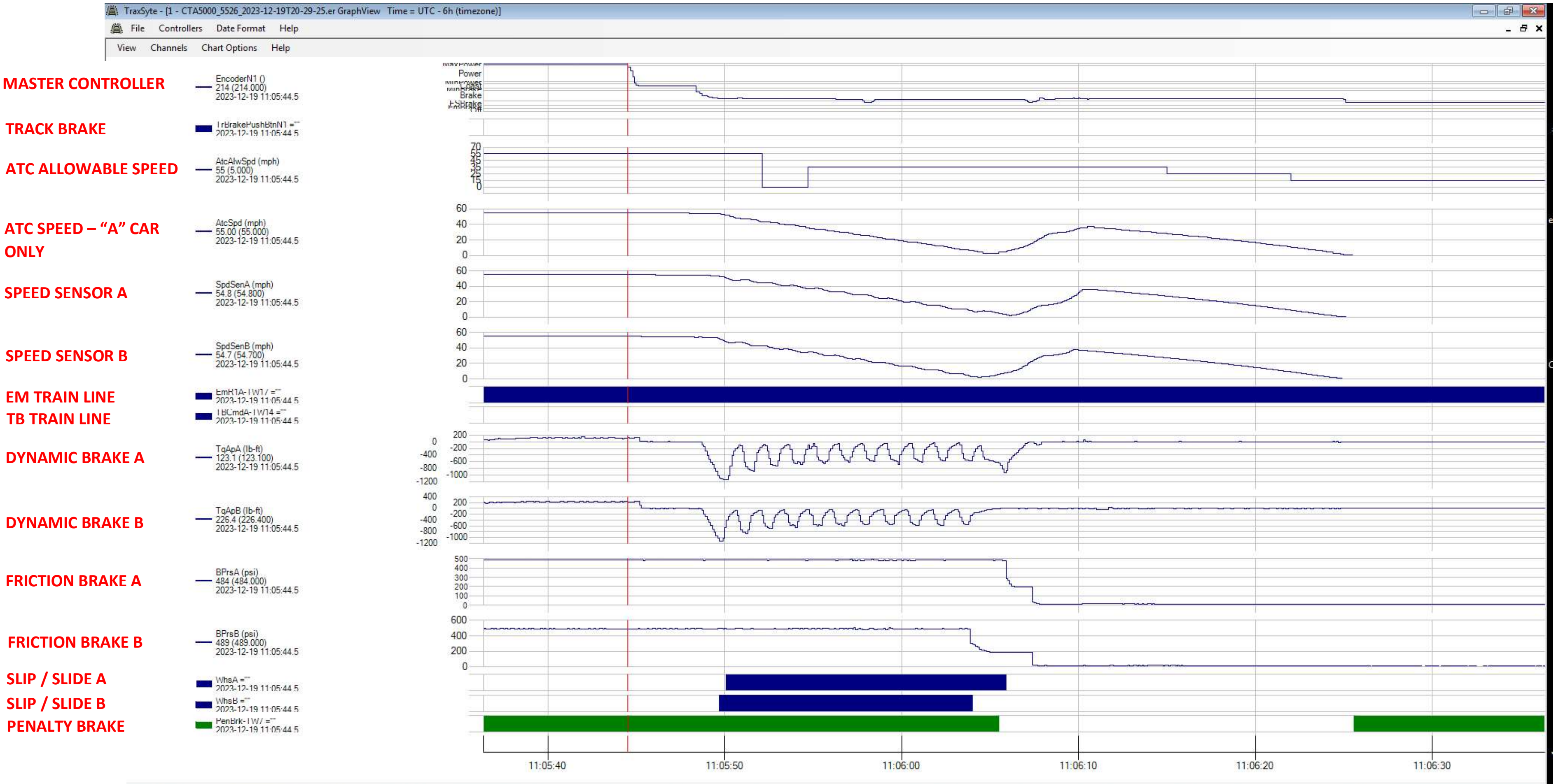
Test Run #2 ERU Event Log – Operator acts normally; full service brake at 26T bond



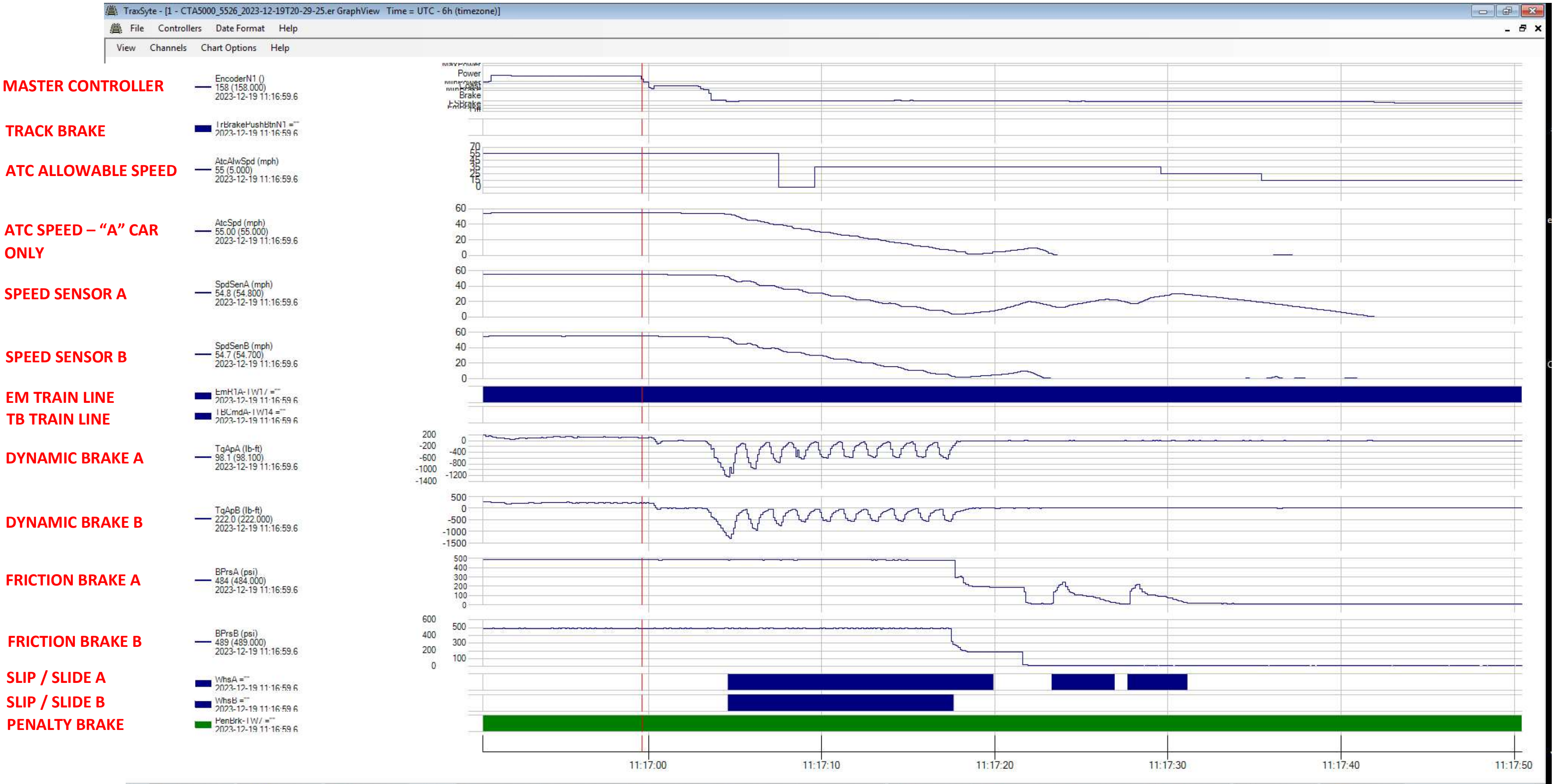
Test Run #3 ERU Event Log – ATC bypass; ~75% service brake at 26T bond



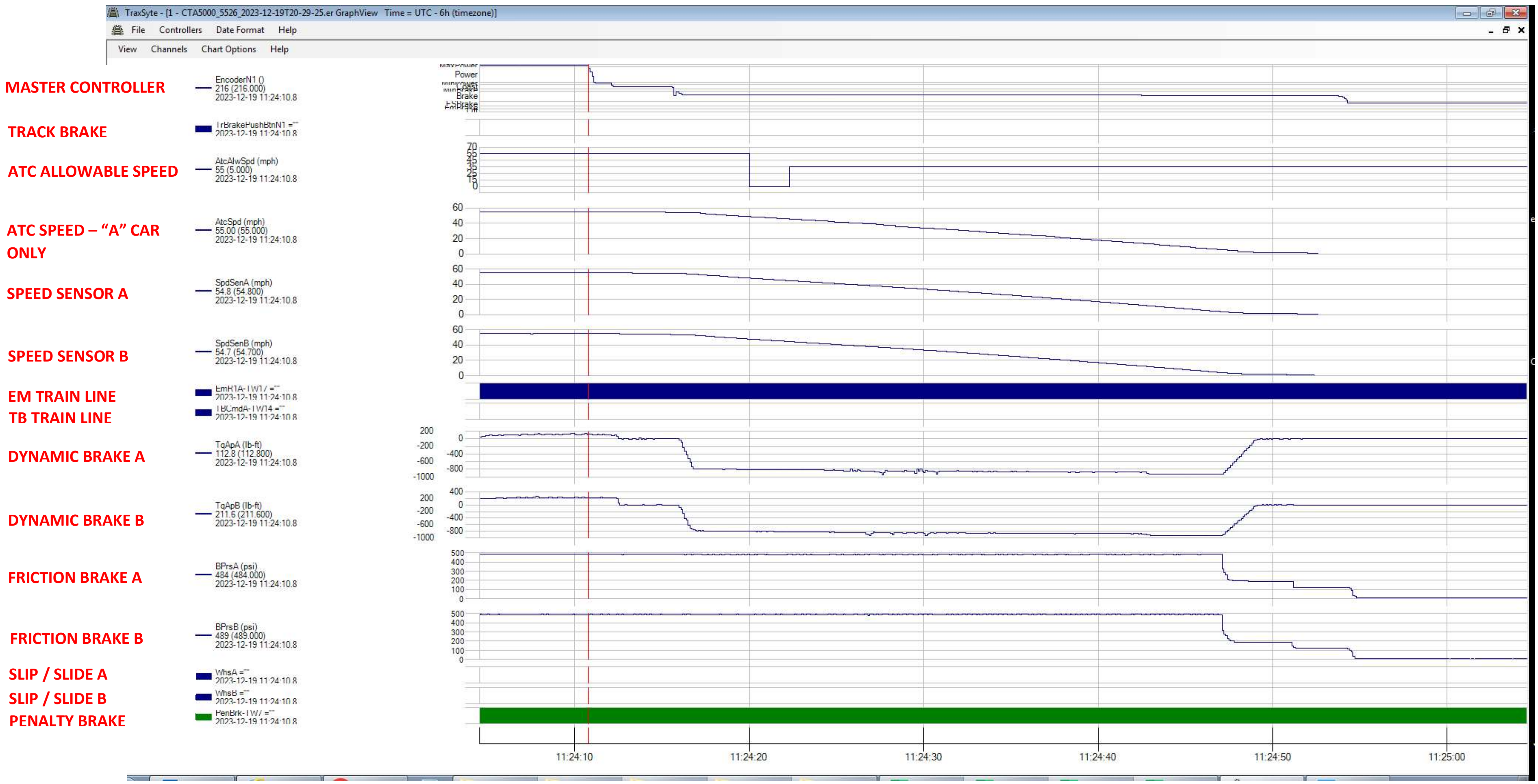
Test Run #4 ERU Event Log – ATC bypass; ~75% service brake at 26T bond



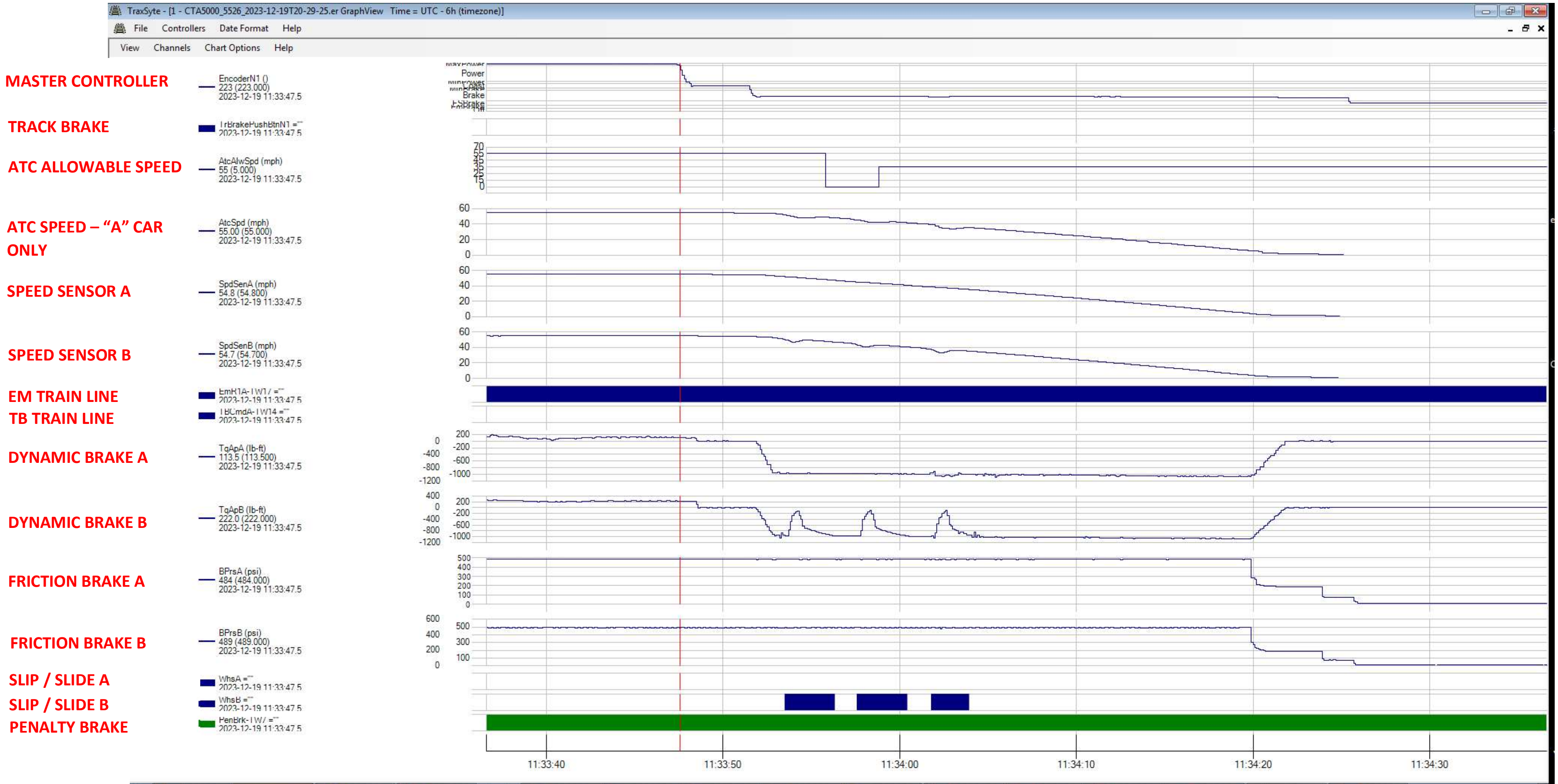
Test Run #5 ERU Event Log – ATC bypass; ~75% service brake at 26T bond



Test Run #6 ERU Event Log – ATC bypass; ~50% service brake at 26T bond – brake rate (-1.7 mph/s)



Test Run #7 ERU Event Log – ATC bypass; ~50% service brake at 26T bond – brake rate (-2.0 mph/s)



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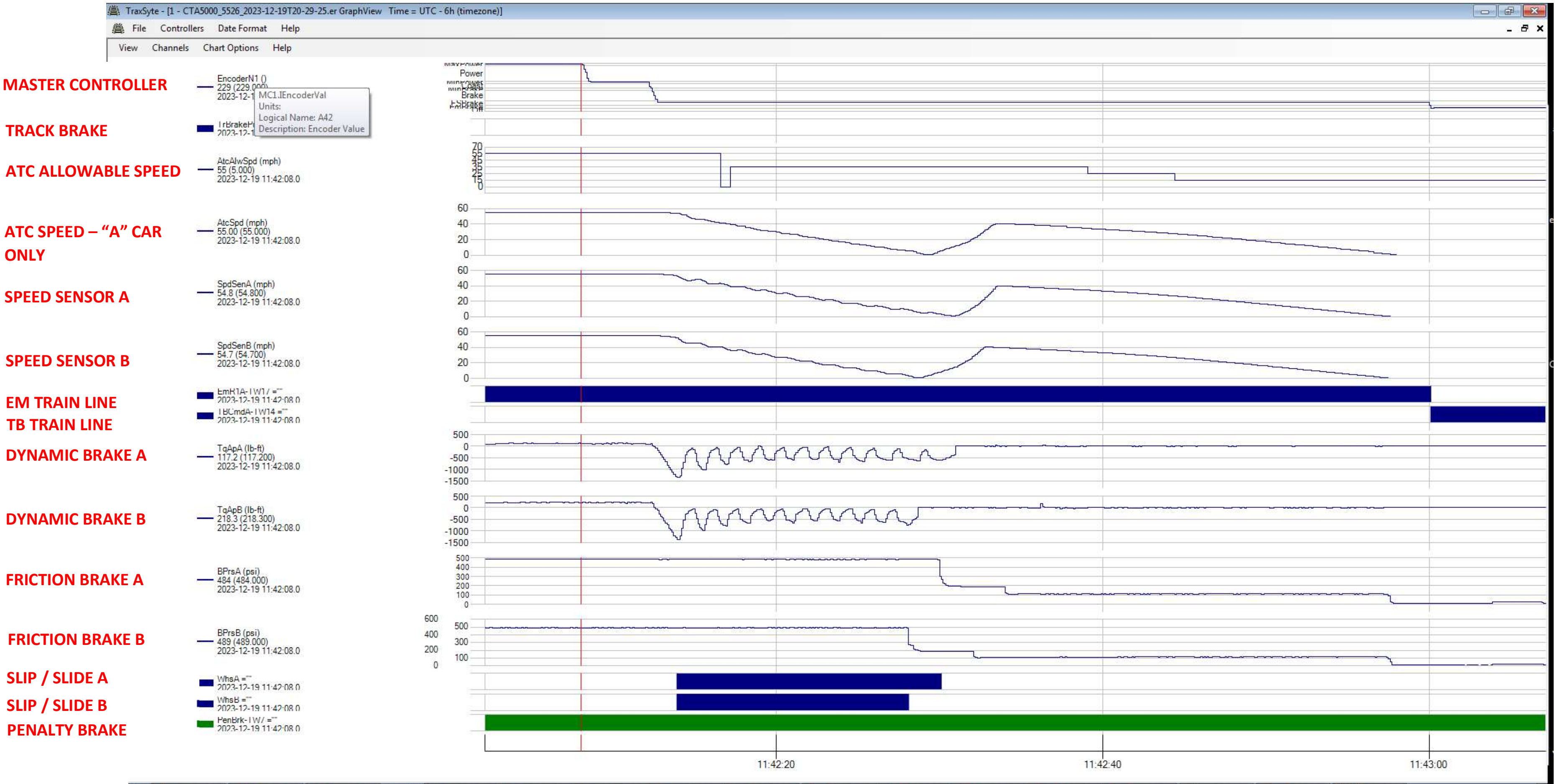
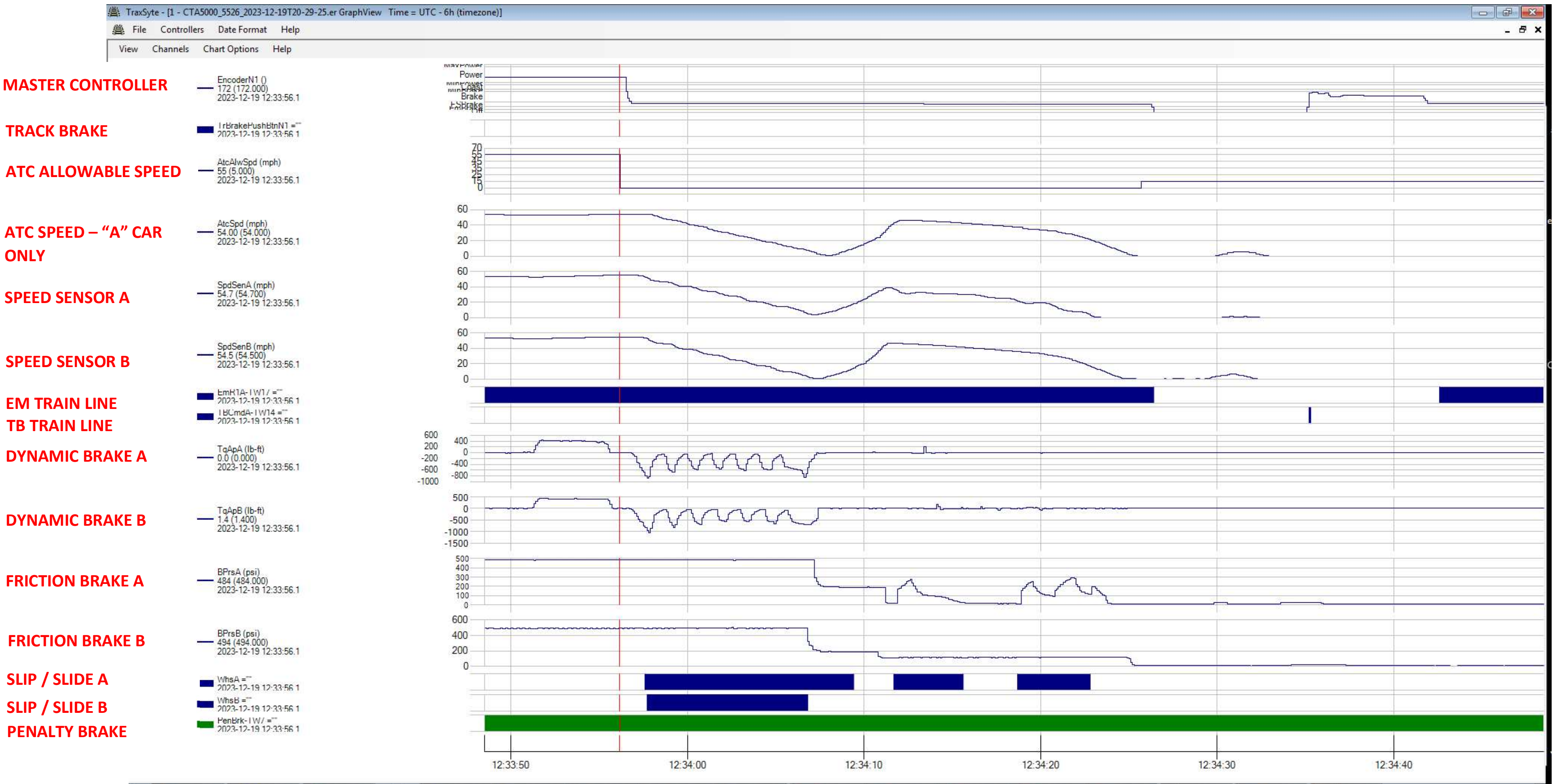
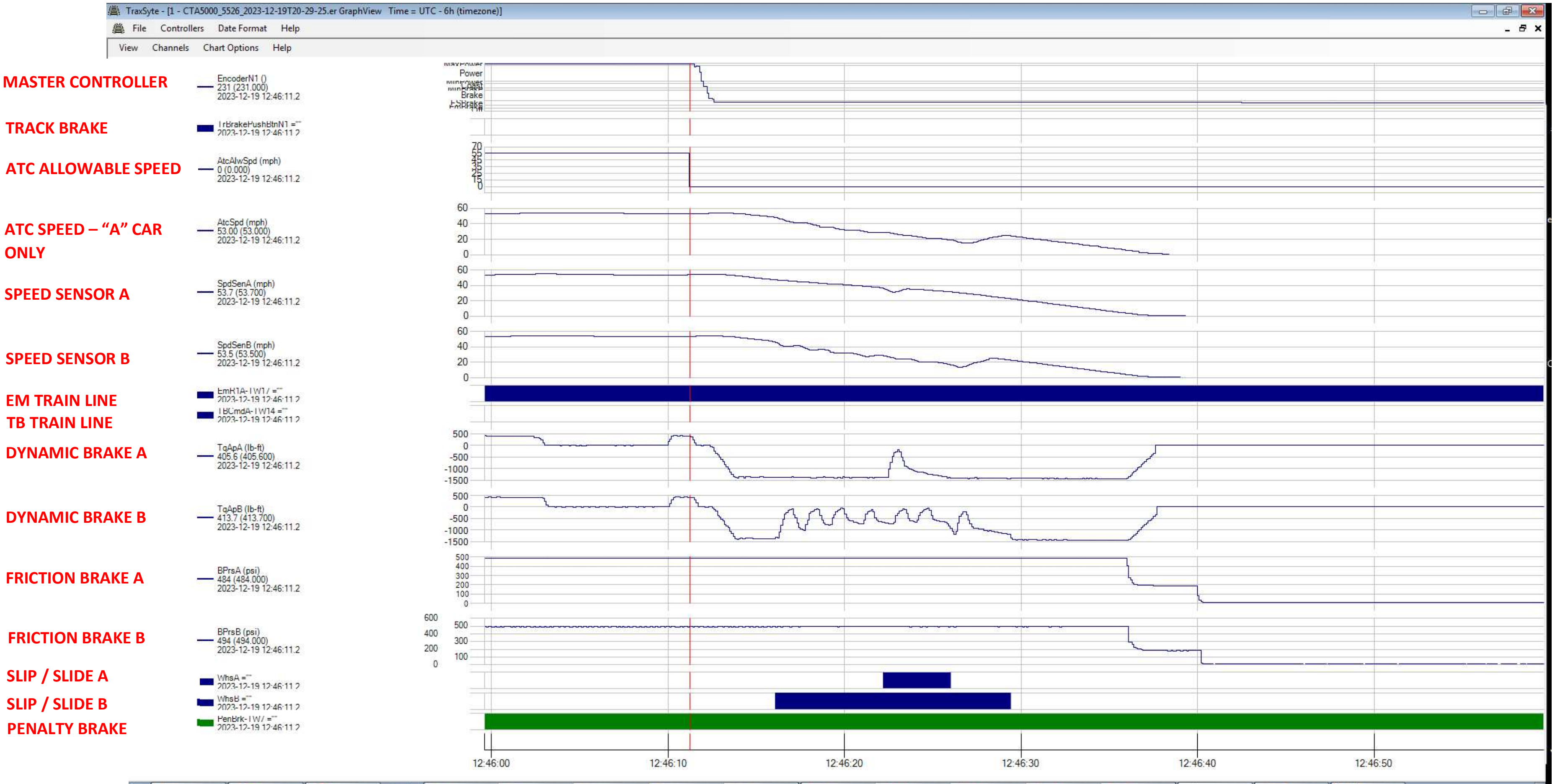
Test Run #8 ERU Event Log – Operator acts normally; full service brake at 26T bond



Test Run #9 ERU Event Log – Incident recreation: operator reacts to ATC; full service brake; "Emergency brake" upon sight of snow-fighter



Test Run #10 ERU Event Log – Incident recreation: operator reacts to ATC; full service brake; "Emergency brake" upon sight of snow-fighter



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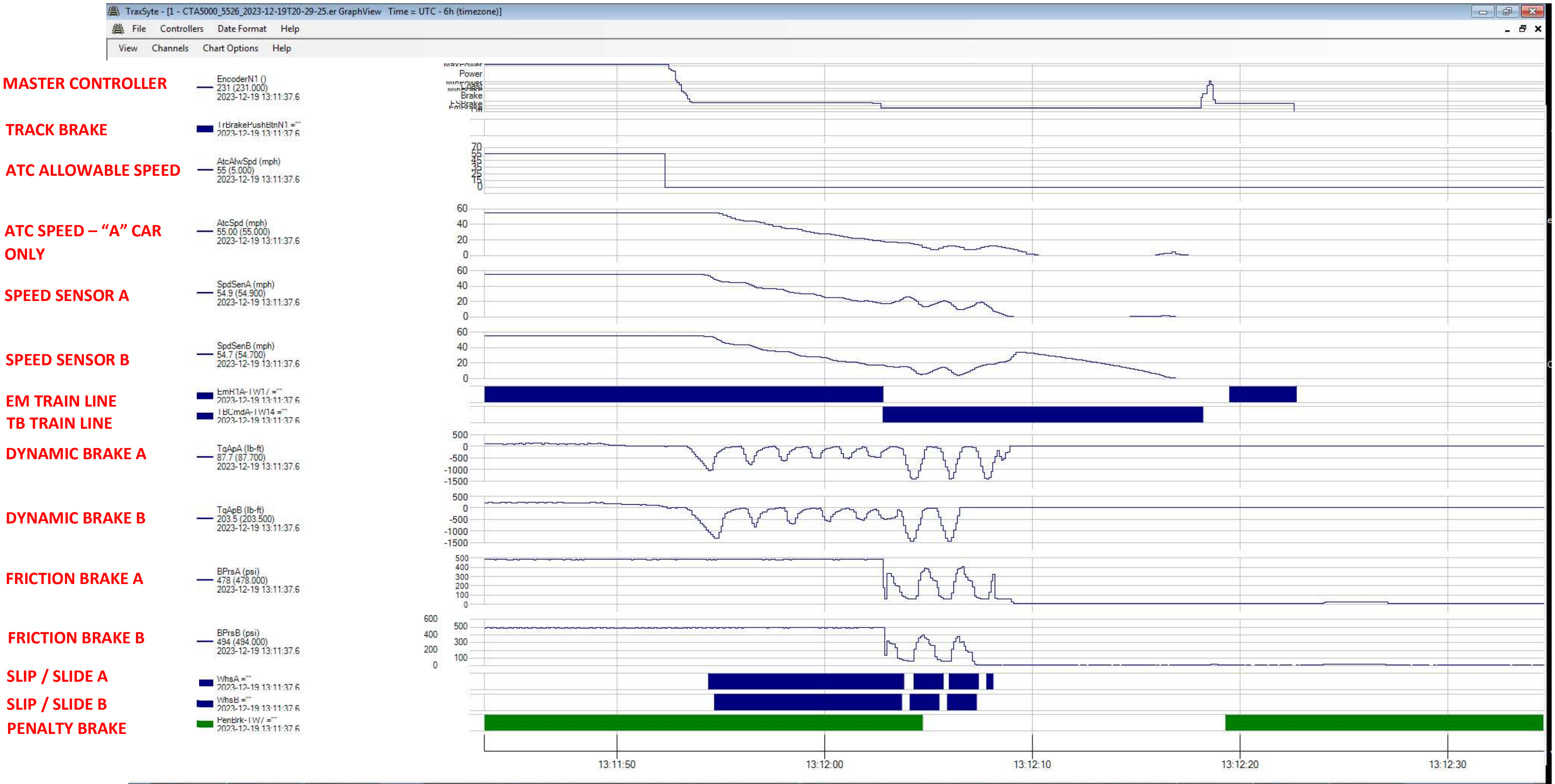
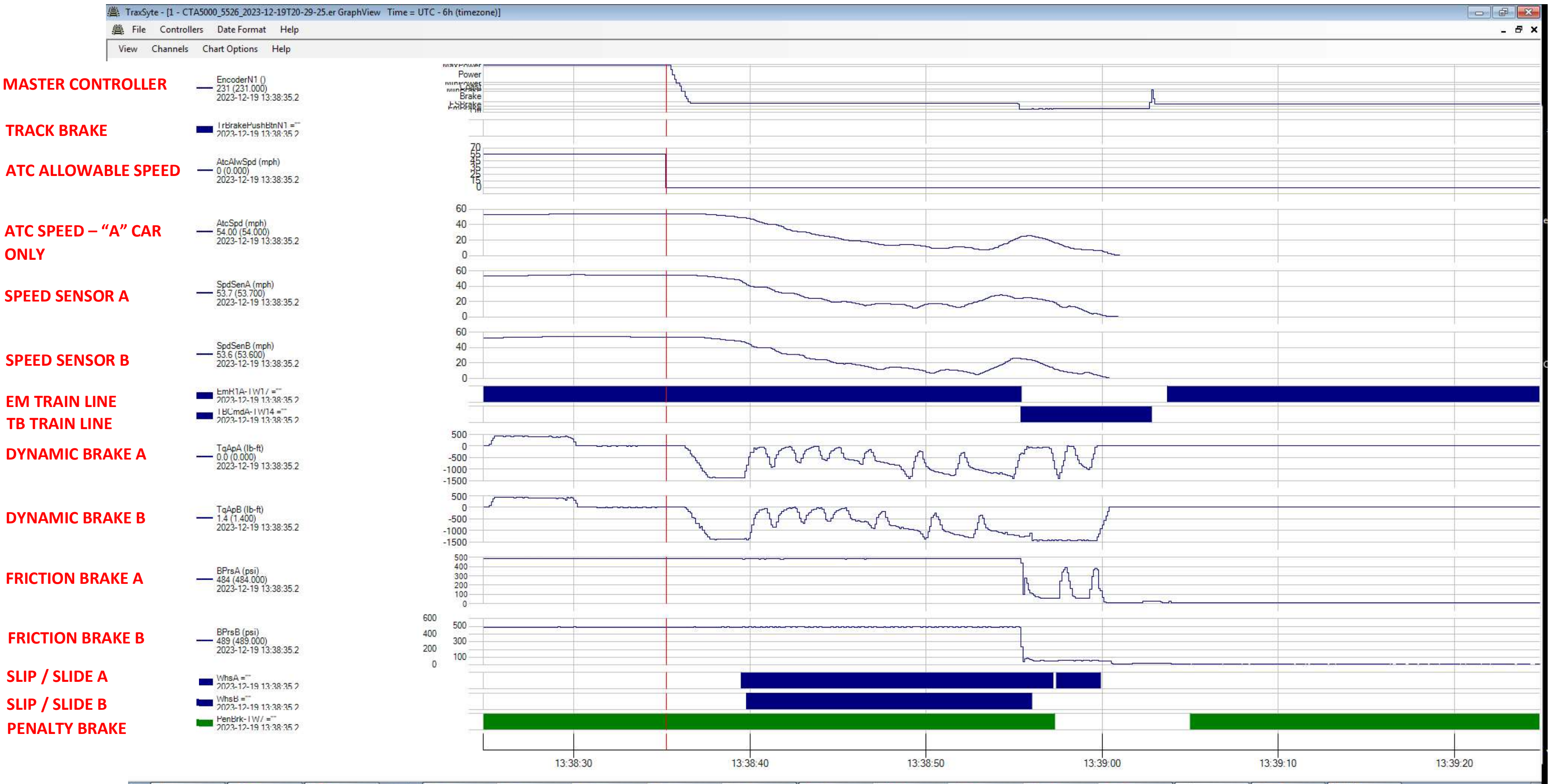
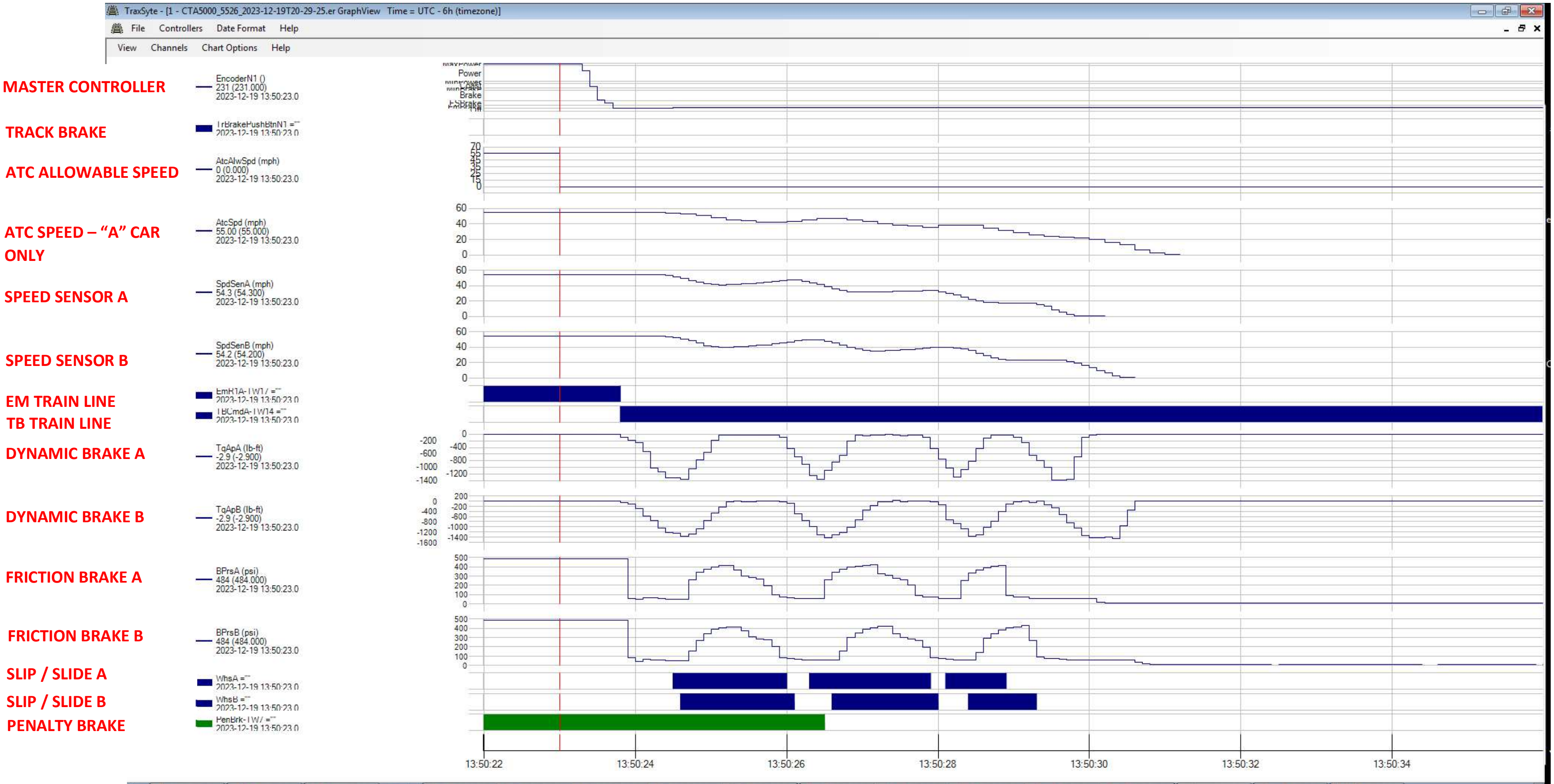
Test Run #11 ERU Event Log – Incident recreation: operator reacts to ATC; full service brake; "Emergency brake" upon sight of snow-fighter



Test Run #12 ERU Event Log – Incident recreation: operator reacts to ATC; full service brake; "Emergency brake" upon sight of snow-fighter



Test Run #13 ERU Event Log – Full emergency at 26T bond



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Test Run #14 ERU Event Log – Full emergency at 26T bond; track brake featured turned ON