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Train Energy and Dynamics Simulator (TEDS) Revenue Service Validation: Volume I Unit Train

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13. ABSTRACT (Maximum 200 words)

The Train Energy and Dynamics Simulator (TEDS) is simulation software, funded by the Federal Railroad Administration (FRA) and developed by Sharma & Associates, Inc. (SA), to study train operation safety and performance as affected by equipment, train makeup, train handling, track conditions, operating practices and environmental conditions. This report describes the validation of the TEDS predictions using data collected from a revenue service unit train. The approach to validating TEDS and the associated acceptance criteria are described and applied.

The analysis of simulated results and their comparison to the measured test data show that TEDS predictions are acceptable. Train speed predictions are within 2–3 mph of the measured speed. Coupler forces, as high as 200 kips, are within ± 20%, and brake system pressures are within 3–5 psi, of measured data. These results clearly establish the ability of TEDS to accurately replicate field events.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

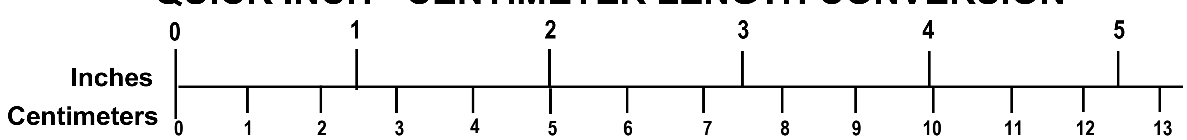
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

The Train Energy and Dynamics Simulator (TEDS) is simulation software, funded by the Federal Railroad Administration (FRA) and developed by Sharma & Associates, Inc. (SA), to study train operation safety and performance as affected by equipment, train makeup, train handling, track conditions, operating practices and environmental conditions. This is Volume I of a two-part project that was performed from June 12, 2013, through June 11, 2016.

TEDS can be used for scenarios consisting of a wide variety of vehicles, track layouts, posted track speeds, train handling and operating conditions. To establish a level of confidence in predicted results, simulation software such as TEDS is required to be validated. Validation generally consists of comparing simulated results with test data measured under realistic field conditions for enough scenarios to gain sufficient confidence.

A series of revenue service tests was conducted for TEDS validation on a unit train of 84 loaded cars pulled by 3 locomotives. The tests covered typical train operating scenarios, such as starting a train from stop and maintaining speed through throttle manipulation and use of automatic air brakes. Bunching and run-out tests were conducted to validate TEDS simulation of slack action. Additional air brake tests, including emergency application, were conducted with the train standing.

Instrumentation collected throttle position, train speed, locomotive power, brake system response and coupler forces in the test train. Data was also collected for input to TEDS simulations.

The following validation acceptance criteria were used:

- Brake pipe and brake cylinder pressure, within ±5 psi
- Train speed, within ±2 mph
- Coupler force, within ±20%

Overall, TEDS speed predictions were found to be accurate. For a track segment of 3.5 miles with six major throttle changes and four air brake applications, the speed predicted by TEDS rarely differed by more than 1 mph from the measured speed during the test. The maximum difference, of about 2.5 mph, occurred during a transient slack adjustment resulting from the initial brake application.

For the bunching and run-out tests, coupler forces measured on the three instrumented cars varied from 120 kips in buff to 220 kips in draft. TEDS accurately predicted the magnitude of the peak run-out force on both Test Car 2 and Test Car 3 at approximately 200 kips, which was within 10 percent of the measured value. TEDS also accurately predicted both the onset and termination of the slack run-out event. The measured and predicted, start and end times matched within 0.5 seconds. These results show that TEDS predicted coupler forces for all three cars met the validation acceptance criteria.

The coupler forces in the slack action and run-in tests varied from 100 kips to 400 kips in buff and up to maximum of 150 kips in draft. TEDS predicted the steady state coupler force magnitudes within the validation acceptance criteria for all three test cars. For example, TEDS predicted 130 kips for the maximum draft force compared to 150 kips measured on Test Car 1.

The timing of the slack action events at each test car were accurately predicted by TEDS. Predicted coupler force magnitudes were close to the measured values, although TEDS tended to under predict the short duration run-in forces associated with the initial impact of the large run-in event.

The air brake application tests included minimum service, partial and full service, and emergency. The brake pipe and brake cylinder pressures on three cars were measured and compared with the results predicted by TEDS.

Although the maximum difference between the measured and predicted pressure for the brake pipe was occasionally as much as 3 to 5 psi for a short time during a transient pressure change, the agreement was generally within 1 psi, which is within the validation acceptance criterion.

Comparison of the predicted and measured values of brake pipe and brake cylinder pressure on each of the three cars agreed well. The differences were within the validation acceptance criterion during transients. The steady-state values were within closer agreement. In addition, TEDS also correctly predicted the effect of insufficient recharge, resulting from a brake application made shortly after a release, on the brake system pressures.

In summary, the simulation of the unit train tests has clearly established the ability of TEDS to accurately replicate field events.

1 Introduction

The Train Energy and Dynamics Simulator (TEDS) is a simulation software developed by Sharma & Associates, Inc. (SA) to study train operation safety and performance as affected by equipment, train makeup, train handling, track conditions, operating practices and environmental conditions. The Federal Railroad Administration funded this effort from June 12, 2013, through June 11, 2016, so that TEDS can be used for scenarios consisting of a wide variety of vehicles, track layouts, posted track speeds, train handling, and operating conditions. To establish the level of confidence in predicted results, simulation software is required to be validated. Validation generally consists of comparing simulated results with data measured under realistic field conditions for enough scenarios to gain sufficient confidence.

1.1 Background

TEDS can be used to conduct safety and risk evaluations, energy consumption studies, incident investigations, train operations studies, ride quality evaluations, new equipment design and current equipment evaluations. Some of the potential TEDS applications are:

- Positive Train Control (PTC) stop distance evaluations
- Motive power optimization for trains and routes
- Incident investigations, energy audits and evaluations of operating rules (current and proposed)
- Safety and performance evaluations for Electronically Controlled Pneumatic (ECP) braking
- Train handling parametric studies and 'cruise control' development for locomotives
- New equipment design evaluation
- Evaluation of the impact of proposed speed limits on rail line capacity
- Rail network simulations

1.2 Objectives

This report documents the planning and execution of a series of revenue service train tests for validation of TEDS. The objective is to quantify the accuracy of TEDS predictions through comparisons of measured data with simulation results from TEDS. This adds to validation that has been previously completed for TEDS [1], using published data, as part of development and documentation.

1.3 Overall Approach

To validate a complex simulator such as TEDS at the system level, three elements are necessary:

1. Acceptance criteria that are defined from an engineering perspective, since it is not possible to exactly match point-for-point measured data in any simulation model
2. Data for subsystem validation that was generated in a controlled environment, such as test rack data from air brakes and impact ramp data from draft gears and cushioning units

3. Data from a revenue service train test for system level validation

The first two elements were used during TEDS development and initial validation [1] [2] [3]. This report addresses the third element: system level validation based on data collected from an instrumented revenue service train.

When validation was defined for the TEDS model [1], the following three criteria were used:

1. TEDS should predict the occurrence of revenue service events.
2. TEDS should predict the timing and trend of various parameters (e.g., coupler force, brake pipe and brake cylinder pressure, vehicle speed, etc.) throughout the event.
3. TEDS should be able to predict the amplitude of the parameters with sufficient accuracy defined as:
    - Significant coupler force peaks should agree within ±20% (significant peaks are those greater than 100,000 lbs.).
    - Steady state (equalized) brake cylinder and brake pipe pressures should agree within ±5 psi. This variance is comparable to the Association of American Railroads' (AAR) certification requirements where equalized cylinder pressure is allowed a ±3 psi variation from the target. However, during transient phases (i.e., when the brakes are being applied or released) it is acceptable for the difference between the TEDS predictions and measured data to be greater than ±5 psi for brief periods.
    - Train speeds should be within ±2 mph. One of the basic validation criteria is that the predicted and measured train speeds should correlate. It is expected that a well thought-out and formulated simulation model, with valid input data, should show a good correlation between the predicted and measured speed.

To understand how the criteria were applied, consider a run-in or run-out event that was due to throttle manipulation or undulating terrain. TEDS should be able to simulate such an event (Criterion 1). There would be a trend in coupler force, represented either by an increase in magnitude or change in algebraic sign such as changing coupler force from draft to buff or vice-versa. TEDS should be able to predict that the event occurs at the same time as a handling or terrain change (Criterion 2).

Predicting the magnitudes of the event's parameters of interest (Criterion 3) is the most difficult criterion to satisfy due to the assumptions that are required to develop the model and linearize, or piecewise linearize, the input data and characteristics, which are often nonlinear. Also, comparing magnitudes of predictions to measured test data is difficult due to the variability and inaccuracies inherent in measurements.

Table 1-1 summarizes the acceptance criteria used for TEDS validation in this report.

Table 1-1. Validation criteria for TEDS coupling, air brake, and vehicle dynamics systems

Parameter	Criterion	Acceptance
Coupler Forces	Occurrence	Predict synchronization in timing and location
	Trend	Show correct trend
	Magnitude	Predict peaks (>100,000 lbs.) within ±20%
Air Brake	Occurrence	Predict synchronization in timing and location
	Trend	Show correct trend
	Magnitude	Predict steady state pressure within ±5 psi
Speed	Occurrence	Predict synchronization in timing and location
	Trend	Show correct trend
	Magnitude	Predict speed within ±2 mph

1.4 Scope

The validation effort consisted of collecting train performance data from an operating revenue train, identifying appropriate events to be used in the validation, simulating those events using TEDS, and comparing the simulation results to the measured events. The comparison used the acceptance criteria laid out in the previous section to validate TEDS.

The testing scope included gathering data for events such as starting the train from rest and maintaining speed using throttle, air brakes and combinations thereof. The scope also included various air brake applications and releases, as well as an emergency application, all performed with the train stationary. Slack bunching and run-out tests were also conducted.

Data was gathered from four locomotives and three cars in the test train.

1.5 Organization of the Report

This report is comprised of the following four sections:

Section 2 details the development of the test plan

Section 3 provides the execution of the revenue service test

Section 4 compares TEDS simulation test data

Section 5 summarizes the findings found in this research

2 Test Plan Development

2.1 Pre-Test Tasks

The Indiana Northeastern Railroad (INRR), a short line railroad operating in northeastern Indiana, northwestern Ohio and southeastern Michigan, hosted the revenue service validation tests performed by SA. Among other commodities, INRR moves corn from local grain elevators to an interchange with a Class I railroad in Montpelier, OH. These trains typically consist of 75 covered hoppers loaded to 286,000 pounds (nominally) each.

2.1.1 Route/Track Selection

The route selected for the validation tests corresponded to INRR movement from a grain elevator to a siding a few miles before the interchange point, about 43 miles altogether.

Since the track profile (elevation) has a significant influence on the simulation results (hence, on the comparison of the simulation results to the test data), INRR provided a track profile from a recent survey of the track. The following track parameters were precisely defined and located:

- Elevations along the track (shown in Figure 2-1)
- Curvature along the track
- Features along the track, such as grade crossings, siding switch points, and mileposts are used to align the track data with the train handling and other data collected during the run

It was decided to collect revenue service data from the top of the hill at mile 5 to mile 48 in Figure 2-1.

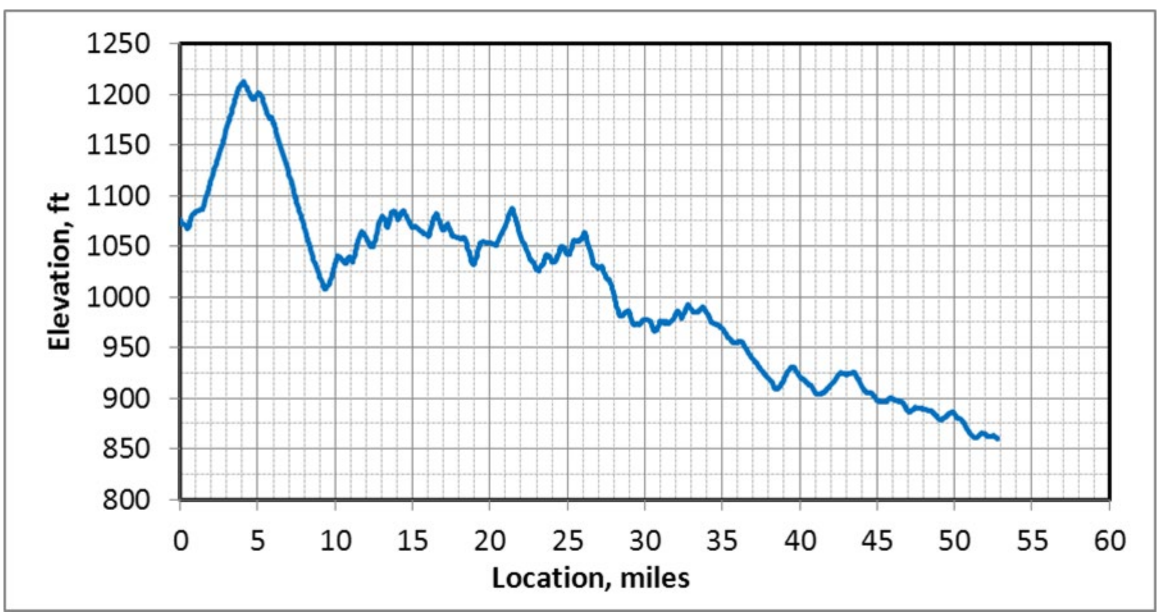

Figure 2-1. Track profile

2.1.2 Pre-Test Simulations

Prior to collecting revenue service train data TEDS was used to simulate the expected test conditions to determine the possible locations where significant events such as run-ins and runouts were expected due to a combination of train handling and track profile. These simulations indicated that coupler forces were expected to remain relatively low throughout the normal revenue run. Consequently, SA requested additional tests involving low-speed movements with throttle and brake manipulation, on a level tangent section of track, designed to generate slack action with significant run-out forces. The engineer was to operate the train normally during most of the revenue run except for these few special requested operations.

2.2 Instrumentation

Several planning meetings were held between SA and INRR at the railroad's shop in Hudson, IN. SA presented test plans and preliminary simulations and discussed the schedule and logistics of the pre-test instrumentation and procedures with INRR for train operation on the days of the tests. Locomotives and test cars were inspected to confirm instrumentation plans.

Figure 2-2. SoMat eDAQ*lite* data acquisition system

A SoMat eDAQ*lite* mobile data acquisition system (Figure 2-2) was used for the test. This rugged and portable system, designed for harsh mobile environments, has extensive on-board signal conditioning and data processing capabilities. Train speed and position were obtained from the SoMat Global Positioning Satellite (GPS) module shown in Figure 2-3.

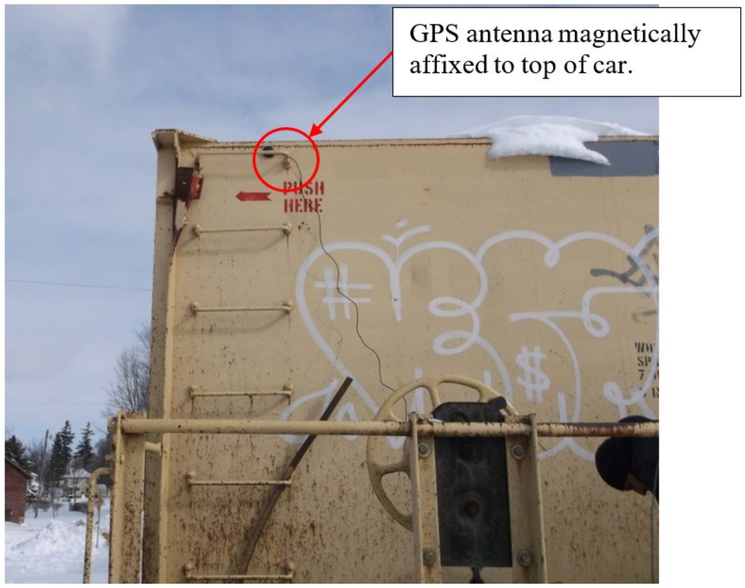

Figure 2-3. GPS antenna installed on Test Car #1

Most of the key parameters, with respect to the track and train, required for simulation are well-defined and do not change within a train operating segment. However, train handling is dynamic and therefore must be captured over the entire section that is to be simulated. SA designed and installed instrumentation to capture the throttle position, brake system pressures, and traction motor volts and amps at each locomotive; as well as coupler force, carbody acceleration, and brake system pressure data on three instrumented cars.

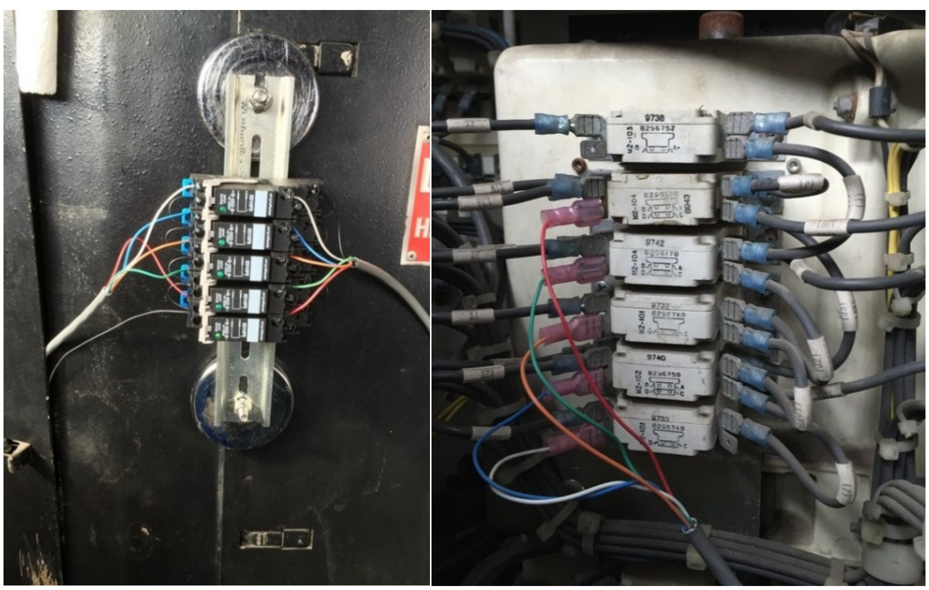

Figure 2-4. Isolation relays (left) and throttle switches (right) and on lead locomotive control stand

The states of five of the controller switches in the lead locomotive's control stand were monitored (Figure 2-4) and subsequently decoded to determine the throttle position, from idle to notch 8. INRR does not use dynamic braking, so this feature was not included in these tests.

An important variable used in TEDS simulations is the tractive effort (TE) produced by each locomotive in the train, so an accurate measure of this parameter is crucial to validation. Since power at the rail is the product of train speed and TE—and since train speed is a measured parameter—locomotive traction power can be used to determine TE. On each locomotive, the power output of a single traction motor was measured and this value was assumed to be representative of all motors on that locomotive. From this data, the locomotive characteristic curves (i.e., TE vs. speed and throttle notch), can be constructed and used by TEDS to estimate the TE as delivered at the rail.

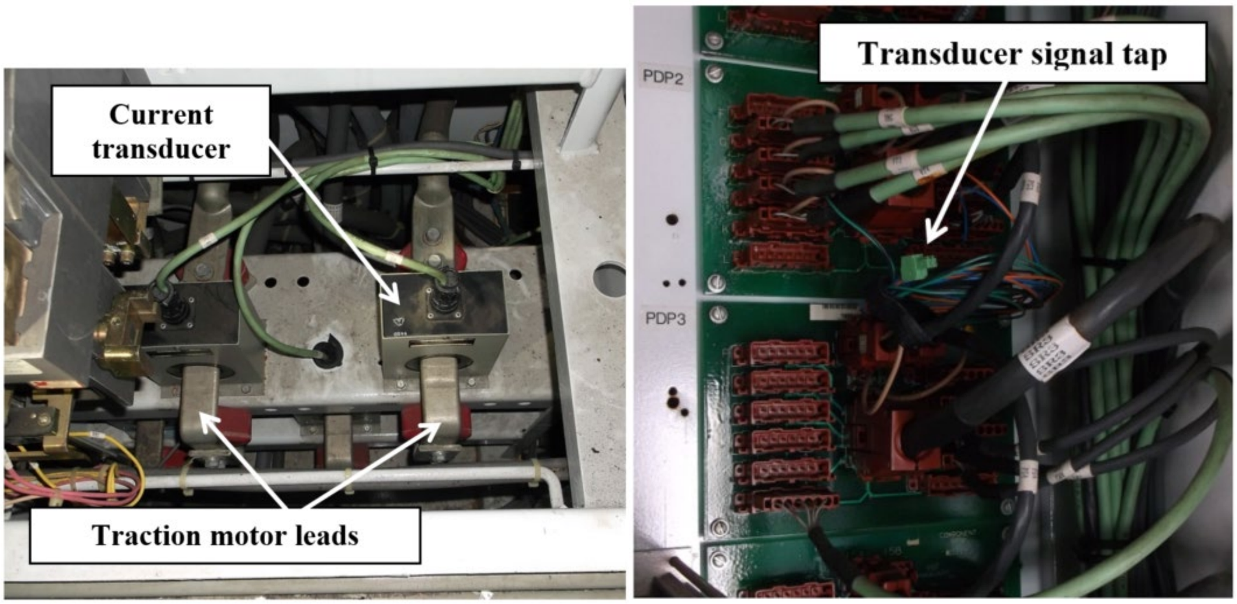

Figure 2-5. Traction motor current transducer and computer patch panel on lead locomotive

The GP-40 control system uses transducers for traction motor current and voltage feedback. SA tapped into the signals from these transducers by stripping insulation from the relevant conductors at the corresponding computer connectors (Figure 2-5). The motor current signal was calibrated by running the locomotive under load, while held stationary with the independent brake, and reading amps from the control stand display. The voltage reading for calibration was taken from the maintenance screen while operating the locomotive at about 20 mph.

The older GP-30 locomotives do not use current and voltage feedback, so the transducer method could not be used. Voltage across one of the traction motors was obtained by connecting to transition contactor terminals in the electrical cabinet. A voltage divider circuit was used to reduce the signal to instrumentation input level (Figure 2-6).

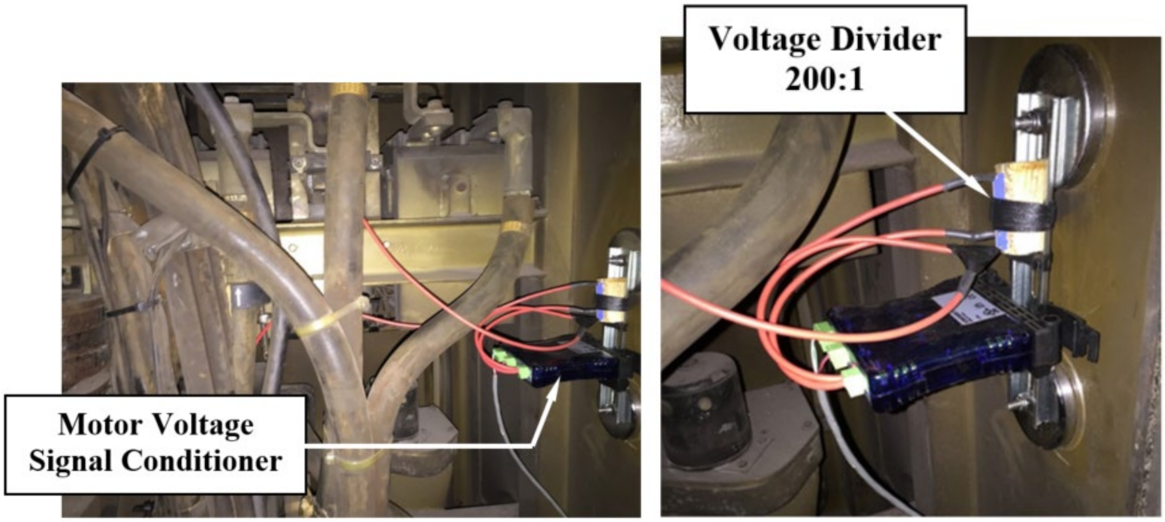

Figure 2-6. Traction motor voltage measurement on GP-30 locomotives

Figure 2-7. Current transducer installed around traction motor lead, GP-30 locomotives

Motor current was obtained using a separate direct current (DC) transducer installed around one of the motor leads (Figure 2-7).

The signals for all locomotive electrical measurements (i.e., motor current and voltage, as well as throttle position switch states) were isolated with signal conditioners to protect the data acquisition equipment.

Locomotive air brake pressures (i.e., equalizing reservoir, brake pipe, and brake cylinder) were accessed via quick-connect test ports on the electronic brake equipment, in the cabinet beneath the GP-40 cab (Figure 2-8).

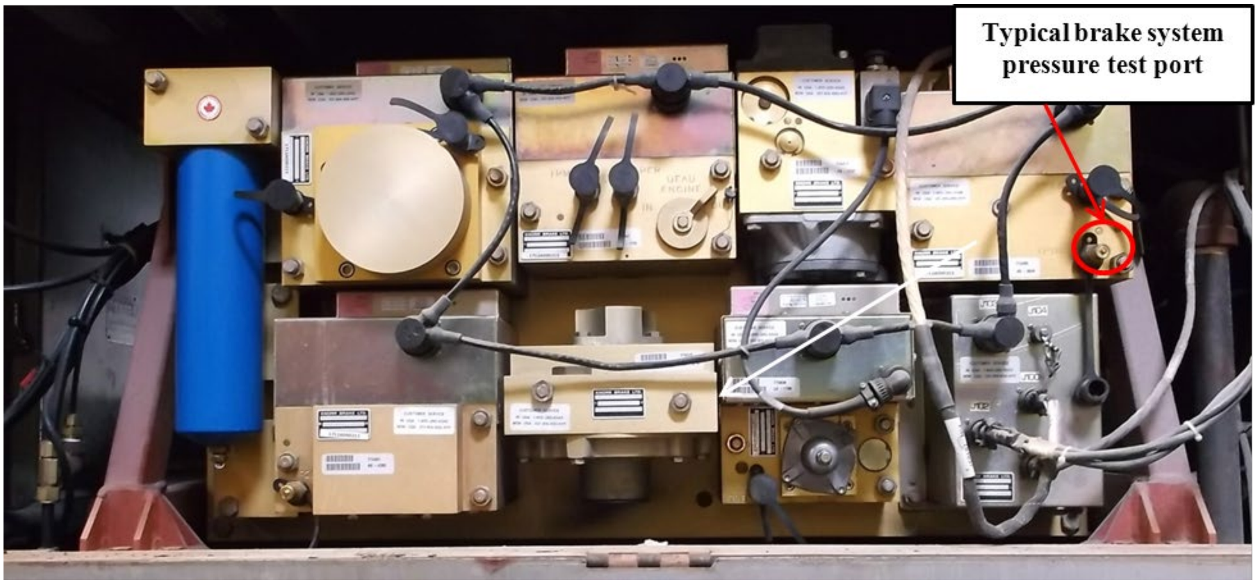

Figure 2-8. Electronic air brake equipment on lead locomotive

All three instrumented test cars had truck-mounted brake systems located at the B-end under the slope sheet. The brake cylinder line on all three cars had an existing test port with a quick connect fitting. Similar (wafer type) fittings were installed at the reservoir connections for auxiliary and emergency pressures. Brake pipe pressure was obtained by drilling into the branch pipe and welding on a saddle fitting with a quick connect test fitting for a pressure transducer (Figure 2-9).

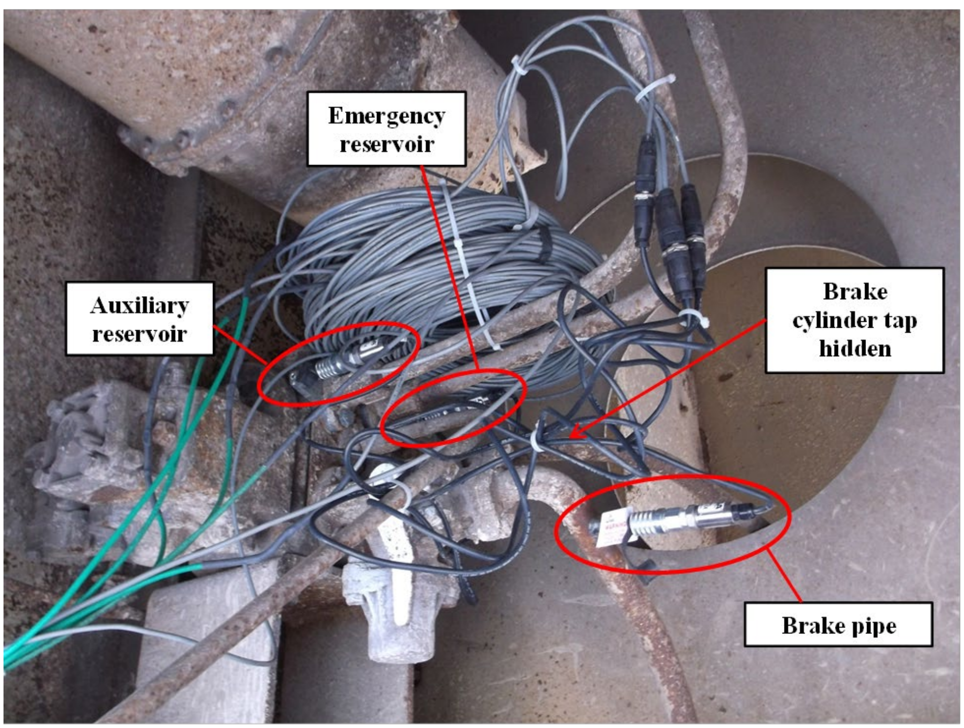

Figure 2-9. Air brake instrumentation on typical test car

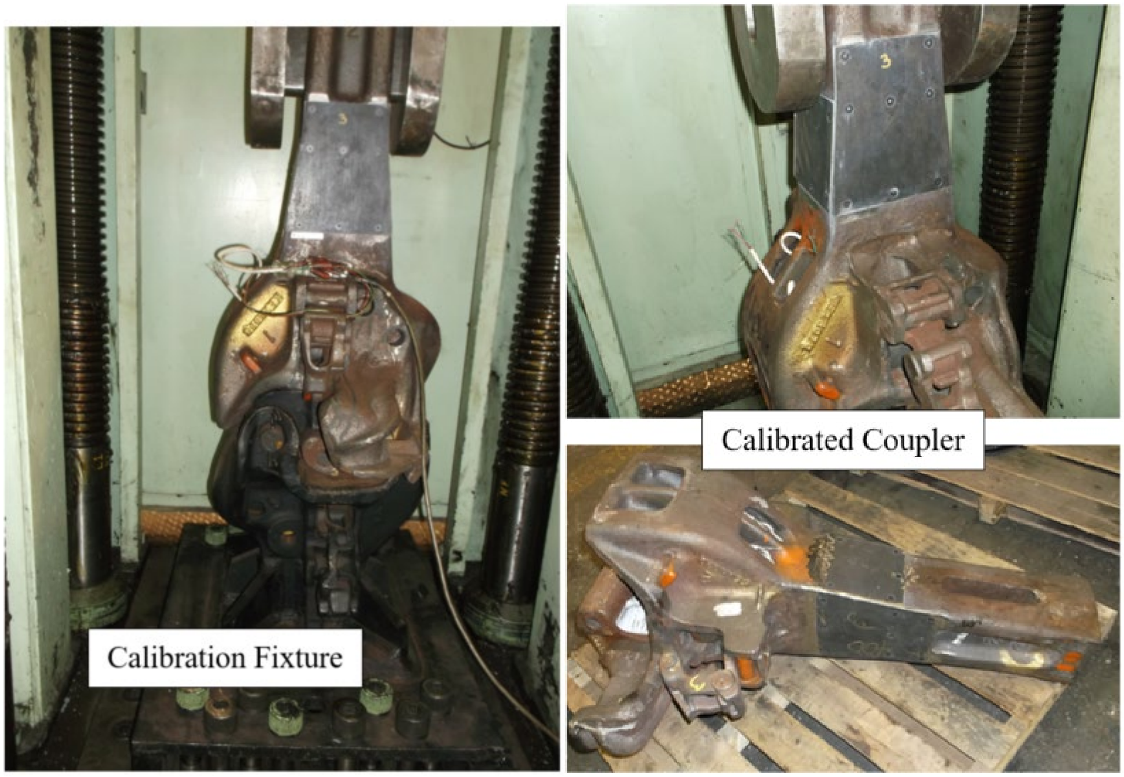

Figure 2-10. Dynamometer coupler calibration

Figure 2-11. Dynamometer coupler installed in Test Car 1 (right)

Figure 2-11 shows the dynamometer coupler installed in Test Car 1 and coupled to the last locomotive in the consist.

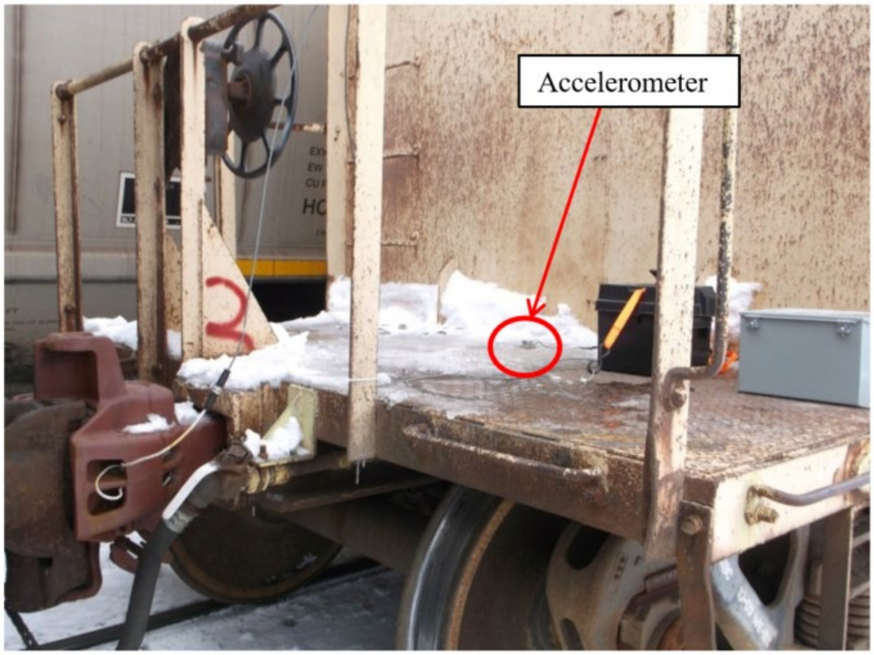

Figure 2-12. Accelerometer installed on typical test car

Coupler forces were measured with dynamometer couplers. Special order, solid-shank couplers were fitted with strain gauges and calibrated in a million-pound load frame (Figure 2-10).

Accelerometers were also mounted on each test car, on the deck just above the center sill, to measure the carbody longitudinal acceleration due to slack action (Figure 2-12).

3 Revenue Service Test Execution

The planned tests were completed in 2-days operation of the test train, in late February 2016. Several inches of snow fell the previous day, so train loading was delayed. The weather on two test days was generally clear and cold, with temperatures in the 15 to 20 °F range. The test train was loaded and assembled on the first test day and departed about 5:00 pm after completion of the initial terminal brake test (see Figure 3-1). It operated approximately 27 miles of the planned route, then was stopped for the night at 6:45 pm. The standing air brake applications and low-speed slack action tests were conducted in the morning of the following day, then the revenue service tests resumed.

Figure 3-1. Test train assembled for initial terminal test, prior to departure

Figure 3-2. Test train, on the morning of the second day, prior to slack bunch and run-out tests

3.1 Test Train Configuration

The test train consist included 4 locomotives, 3 test cars, and 84 covered hoppers (Figure 3-2). All cars were loaded. The hoppers were loaded with corn and the test cars were loaded with gravel. The first three locomotives were on-line (providing traction), the fourth was included as a spare. The fourth locomotive's engine was idling, but traction was isolated. Air brake multiple unit (MU) hoses were connected, so the fourth locomotive participated in braking.

Train consist:

- GP-40-3; 3,000 hp (DOTX-2000)
- GP-30; 2,250 hp
- GP-30; 2,250 hp
- GP-7 (isolated)
- Test Car #1, instrumentation end facing forward
- 42 covered hopper cars
- Test Car #2, instrumentation end facing backward
- 21 covered hopper cars
- Test Car #3, instrumentation end facing backward
- 21 covered hopper cars

Overall train characteristics:

- 7,500 hp
- 12,300 trailing tons
- 5,400 feet total length

Hopper car loadings were obtained from the shipper. Weights of the test cars, as loaded with gravel, were obtained from INRR. Figure 3-3 and Figure 3-4 illustrate the distribution of vehicle weights and lengths, respectively, in the simulated train.

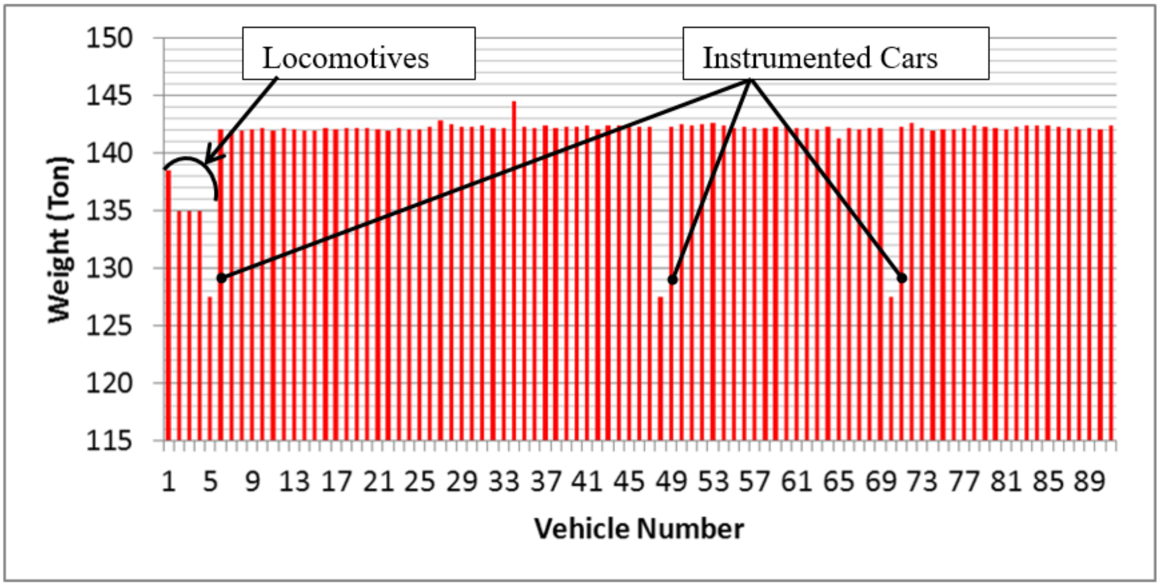

Figure 3-3. Vehicle weight distribution, simulated test train

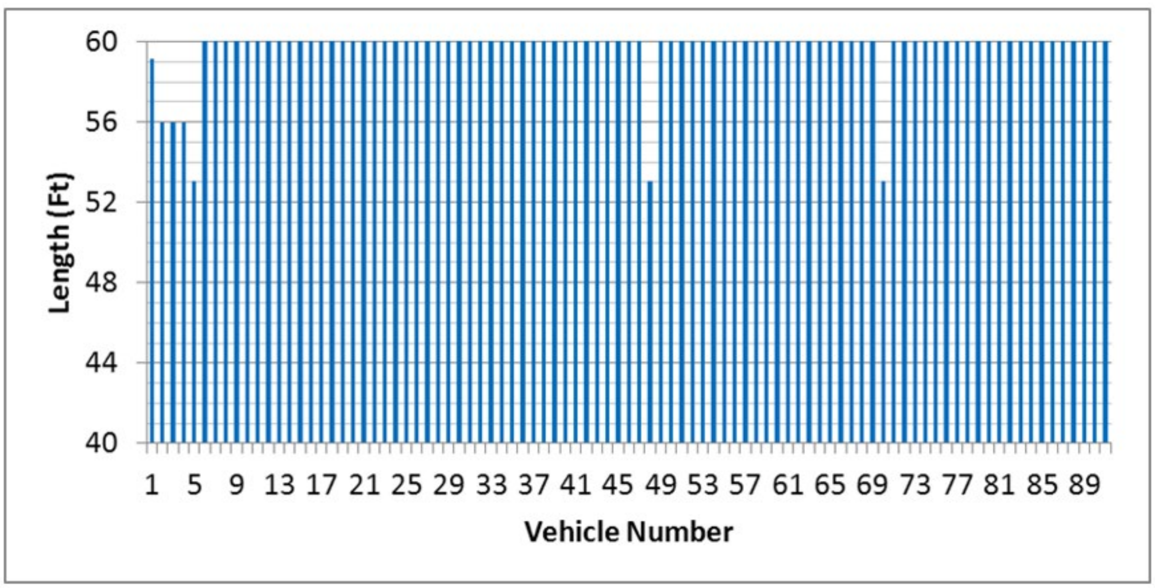

Figure 3-4. Vehicle length distribution, simulated test train

The brake pipe regulating pressure was 90 psi and the air flow rate to compensate for system leakage was minimal. The air flow display on the engineer's control panel changed directly to zero after reducing below a value of 17 cfm, and no intermediate value was displayed. An assumed air flow value of 5 cfm was used in the simulated train. None of the locomotives was equipped with dynamic braking. The hopper car brake systems had ABDX control valves, whereas the test (gravel) cars had ABD control valves. The lead locomotive was equipped with an electronic brake system, while the three trailing locomotives had conventional 26-L type pneumatic brake systems. Braking ratios of 10 percent for all cars and 28 percent for the locomotives were assumed in the simulated train.

The separation between coupler heads in mated coupler pairs was measured in two strings of hopper cars that were standing on sidings waiting to be assembled into the train; one string was stretched (in draft) and the other string was bunched (in buff), as shown in Figure 3-5. Typical coupler separation difference between buff and draft conditions was about 1.5 inches. So, assuming the draft gears were not compressed, the total free slack per connection was at least 1.5 inches. Accounting for additional slack in the other draft components (e.g., draft key slot in coupler shank, yoke, etc.), the simulated train was assumed to have 1 inch of free slack at each end of each car. Standard metal draft gear was assumed for all vehicles in the simulated train.

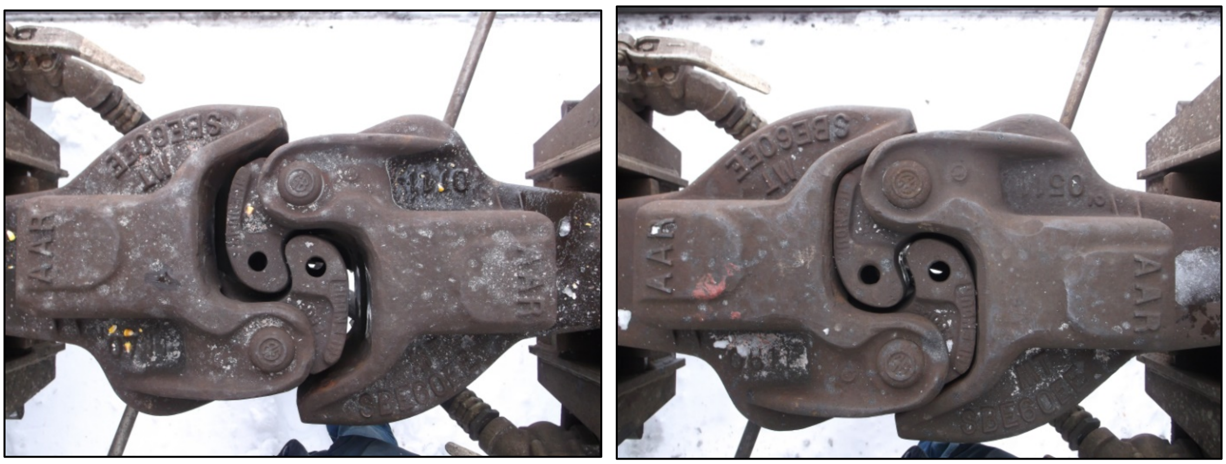

Figure 3-5. Couplers in draft (left) and buff (right) conditions for estimating free slack in the train

3.2 Data Collection

Three INRR gravel cars, serving as instrumentation test cars, were distributed within the test train consist. Each of the test cars was equipped with a stand-alone SoMat data acquisition system powered by its own 12V battery, which avoided the complication of running cables between cars (Figure 3-6). Data from the locomotives was collected by the SoMat system on Test Car #1, located directly behind the last locomotive in the consist. A diagram of the train configuration with instrumentation is shown in Figure 3-7.

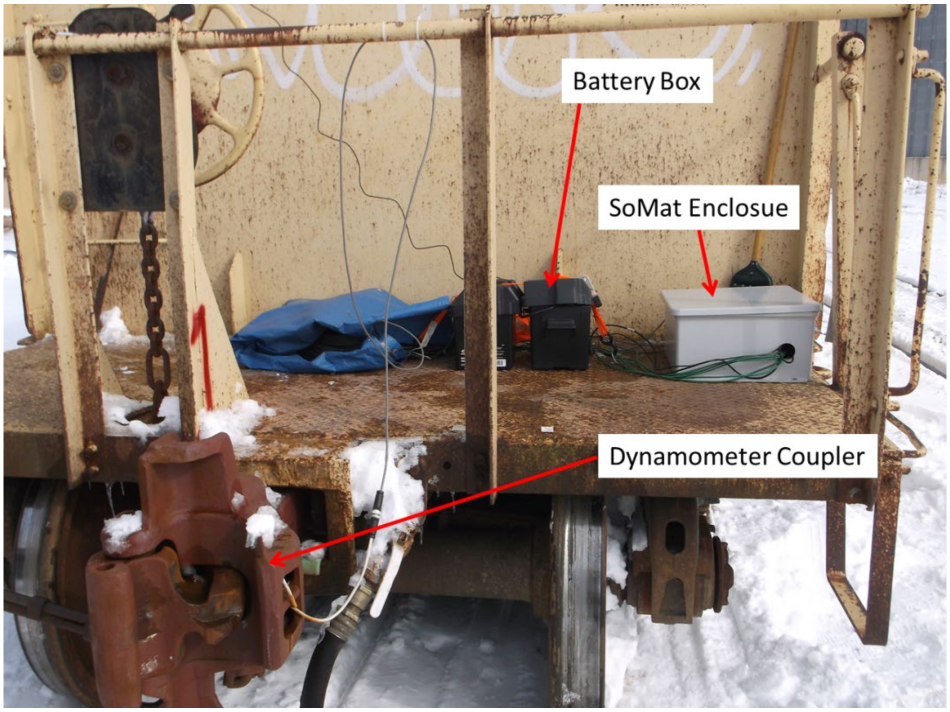

Figure 3-6. Data acquisition equipment on a typical test car

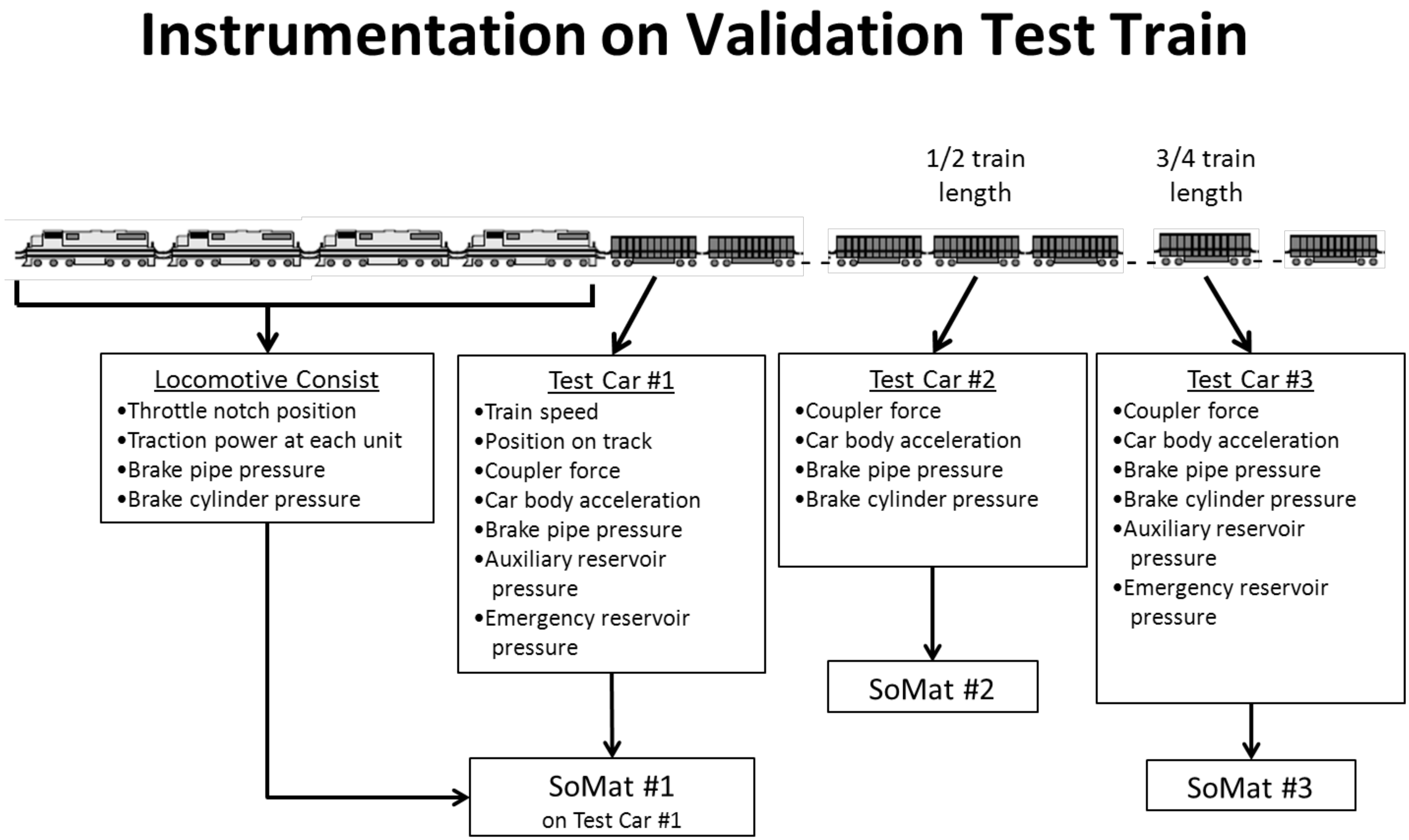

Figure 3-7. Instrumentation installed on the test train

Details of the physical measurements collected are listed in Table 3-1. The speed and position (latitude and longitude) measurements were sampled every second. All other data was collected at 200 samples per second, and the analog parameters were filtered at 67 Hz.

Table 3-1. Test train instrumentation

Measured Parameter	Locomotive(s)	Test Car 1	Test Car 2	Test Car 3
Speed (GPS)		XX		
Lat-Long position (GPS)		XX		
Brake pipe pressure	Lead unit only	XX	XX	XX
Brake cylinder pressure	Lead unit only		XX	XX
Auxiliary reservoir pressure		XX		XX
Emergency reservoir pressure		XX		XX
Fore end coupler force		XX		
Aft end coupler force			XX	XX
Longitudinal acceleration		XX	XX	XX
Throttle position	Lead unit only			
Traction motor #2 volts	Active units			
Traction motor #2 amps	Active units			

('**XX**' in cell indicates vehicle has corresponding instrumentation.)

Originally, the plan was to collect the equalizing reservoir pressure on the lead locomotive and the brake cylinder pressure on Test Car #1, but recording of these data was not successful. In addition, the channel collecting traction motor amperage on the lead locomotive failed.

An SA employee rode in the test train lead locomotive cab to take notes during the test, create landmark identification records in the test data, assist the engineer with the interpretation of the special test procedures, and collected other information to help inform an accurate interpretation of the test data and provide appropriate input to the post-test validation simulations.

As each SoMat system was initialized, the time data collection started was recorded. This allowed data from the separate systems to be synchronized with each other to within approximately 1 second. A further level of synchronization was obtained, after data collection had begun, using the accelerometers present on each system. Pairs of accelerometers from separate systems were held together and then quickly turned upside down. This created identical square wave pulses on the separate data records providing a means of synchronizing the systems to within a few hundredths of a second.

At the end of the test run, the instrumentation cars were cut out of the train, the data collection was halted, and the data was downloaded from the SoMat systems to a portable computer. Post processing of the data included appropriate filtering of each channel, and alignment of the data streams from the three separate SoMat systems using the synchronization scheme described above.

Since traction motor current at the lead locomotive was not available, the TE exerted by this locomotive could not be independently determined. Hence, the nominal traction characteristics of a GP-40 type locomotive, available from the TEDS library, were used in the simulations. For the two GP-30 locomotives, the collected traction motor data was used to create tables of their TE characteristics as a function of speed and throttle notch (i.e., over the range of operating conditions in this test).

3.3 Special Tests

In the morning of the second day of testing, before resuming the revenue service test, several special tests were conducted. While the train was still parked, a series of air brake applications and releases was performed for validation of the TEDS air brake model. Air brakes were then applied, locomotive brakes bailed off, and the throttle advanced up to notch 4 to characterize zero speed TE for the consist (for these low notches). Air brakes were then released and a series of low speed movements in alternating directions were performed to generate slack action and significant run-out forces.

3.3.1 Air Brake Tests – Standing Train

The following air brake operations were conducted with the train standing (zero speed) on level track.

1. Observed that the stabilized air flow reading with a fully charged system was slightly less than 19 cfm
2. Minimum reduction was made, equalizing reservoir pressure to 83 psi, and held for about 90 to 120 seconds after the sound of air exhaust in the cab had ceased
3. The application was intensified, equalizing reservoir pressure to 76 psi, and held for about 90 to 120 seconds after the sound of exhaust in the cab had ceased.
4. Released the brakes and recharged the system until the flow meter returned to 19 cfm
5. Made an immediate reduction to 76 psi equalizing reservoir pressure, and held until after exhaust had ceased, as above
6. Released the brakes. The flow quickly built to a maximum of 153 cfm, and then subsided to 60 cfm in about 10 seconds. Continued charging until flow returned to 19 cfm
7. Made a full-service application, equalizing reservoir pressure to 64 psi. Held, as above, until after the exhaust ceased.
8. Released the brakes. Flow quickly built to a maximum of 170 cfm, and then subsided to about 87 cfm at 30 seconds, then 67 cfm at 60 seconds. At that time (60 seconds after release), another full service (equalizing reservoir pressure to 64 psi) was made and held as before until after the exhaust ceased.
9. Released the brakes and recharged the system until flow returned to 19 cfm
10. Made an emergency brake application
11. Released the brakes as soon as the interlock cleared (followed messages on the control stand display). Flow immediately pegged at 176 cfm and remained pegged until brake pipe pressure reached about 69 psi.

3.3.2 Slack Action Tests

With train brakes released, the engineer pushed back, increasing throttle from idle to notch 4, until the speed was about 5 mph. He then moved the throttle to idle and applied the independent brake to stop the train. In the cab, some mild lurching was felt as the cars ran out.

A minute or so after coming to a stop—waiting for the train slack to settle down—the engineer pushed back again to bunch the slack. After reaching about 5 mph, the throttle was reduced to idle letting the train drift, slowly decelerate and finally stop. The engineer then went forward, notching up quickly to as high as notch 6 while still at low speed to generate run out forces. After reaching 5 mph, the throttle was again moved to idle and a full independent brake application was made to stop the train, thereby creating slack run in throughout the train.

4 TEDS Simulations and Comparison to Test Data

After the testing was completed and the data was inspected, the following events of interest were identified:

1. Train startup with speed control on descending grade using air braking
2. Reverse move from a stopped position, with bunching and run-out
3. Train start up with slack action including run-out, then run-in
4. Air brake system applications and releases, including an emergency application

It should be noted that the charts plotting the TEDS simulation results against distance use the location of the specific car corresponding to the parameter plotted. Time-based data was synchronized among the three SoMat data collection systems, as described in Section 3.1.

All track locations are given in miles from an arbitrary zero well behind the starting train location.

4.1 Train Startup and Speed Control

The train negotiated a long descending grade just after its initial startup. The air brake was used for speed control as none of the locomotives were equipped with functioning dynamic braking. The throttle position, brake pipe pressure, elevation profile, and measured speed over this 4-mile segment are shown in Figure 4-1. The large magnitude, but spiky, drops in the brake pipe pressure shown in Figure 4-1 between mile 5 and 5.5 are not real, and are likely due to transducer signal dropout.

The measured speed is compared to the speed predicted by TEDS in Figure 4-2. The speed match between the TEDS prediction and the measured speed is excellent, with the difference rarely exceeding 1 mph. The maximum discrepancy, of about 2.5 mph, occurred during a transient slack adjustment caused by the initial brake application. The match between TEDS predicted speed and the measured speed is within the validation acceptance criterion laid out in Section 1.3.

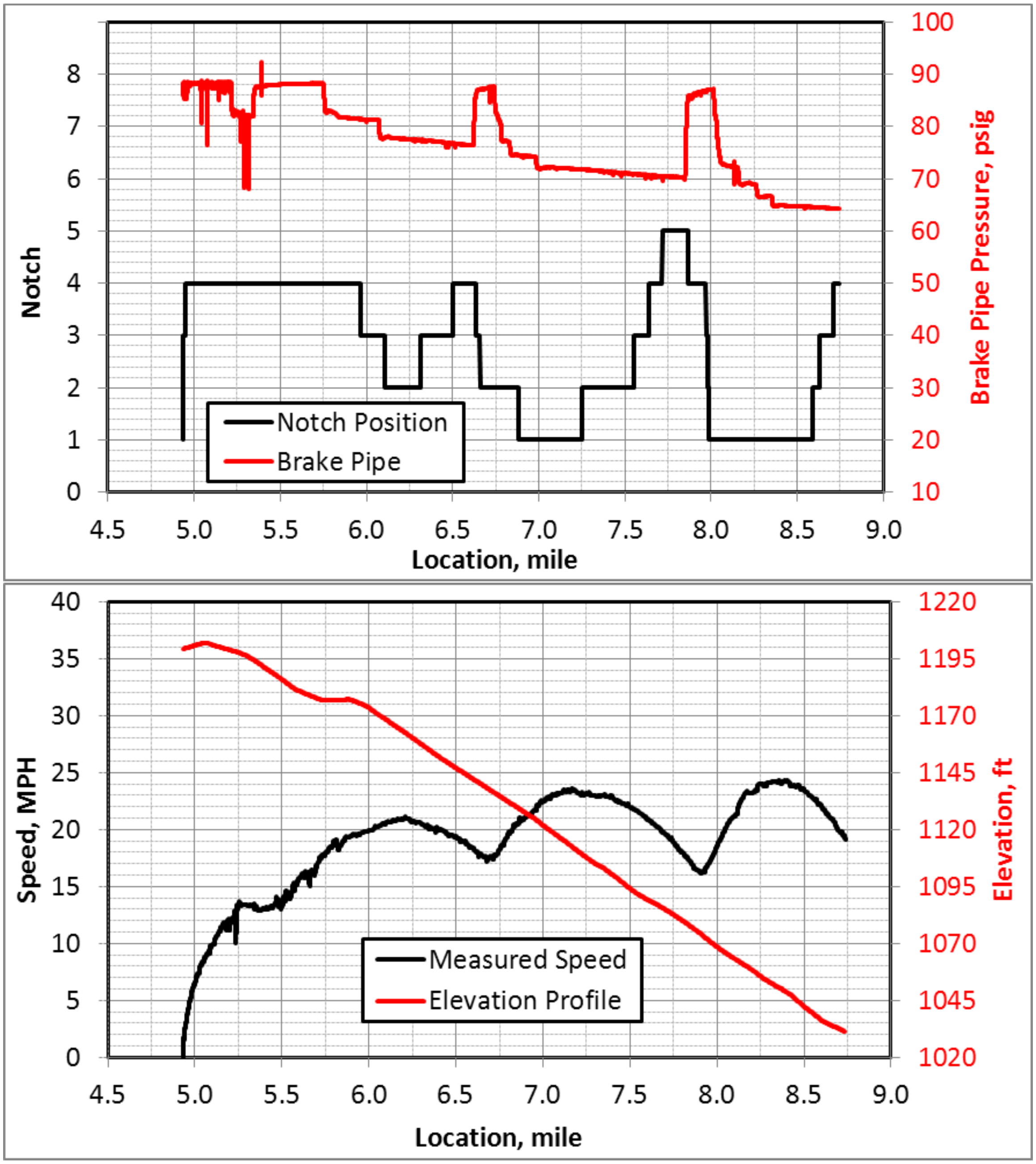

Figure 4-1. Train handling, measured speed and track profile for the initial train startup and speed control test

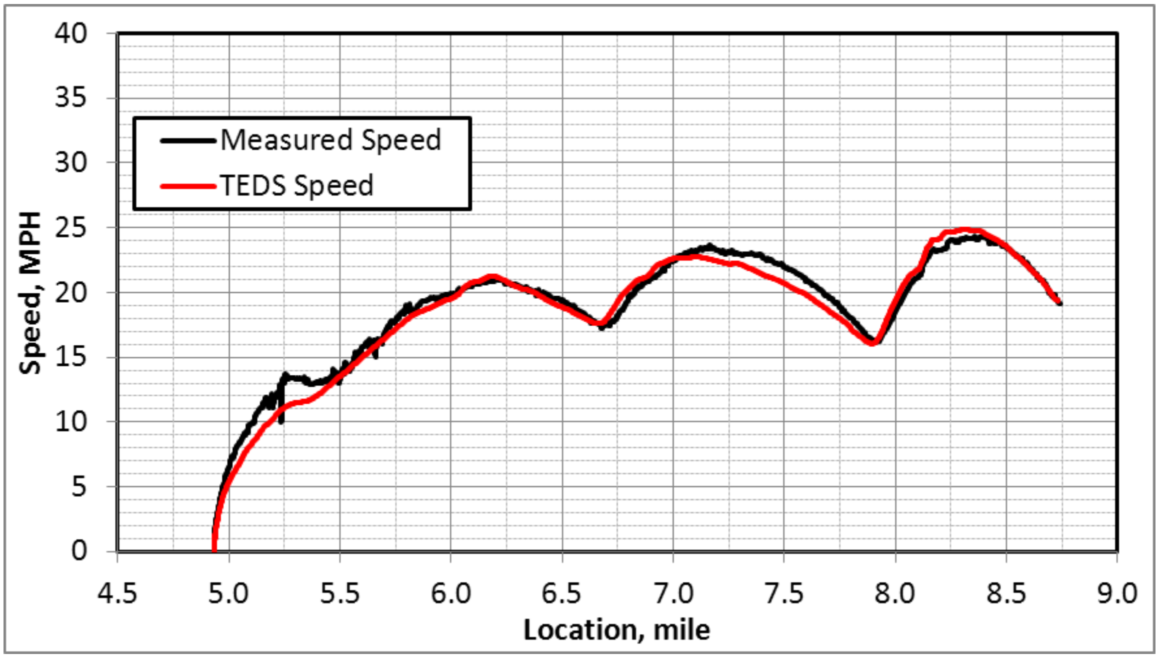

Figure 4-2. Measured and predicted speeds for the initial train startup and speed control test

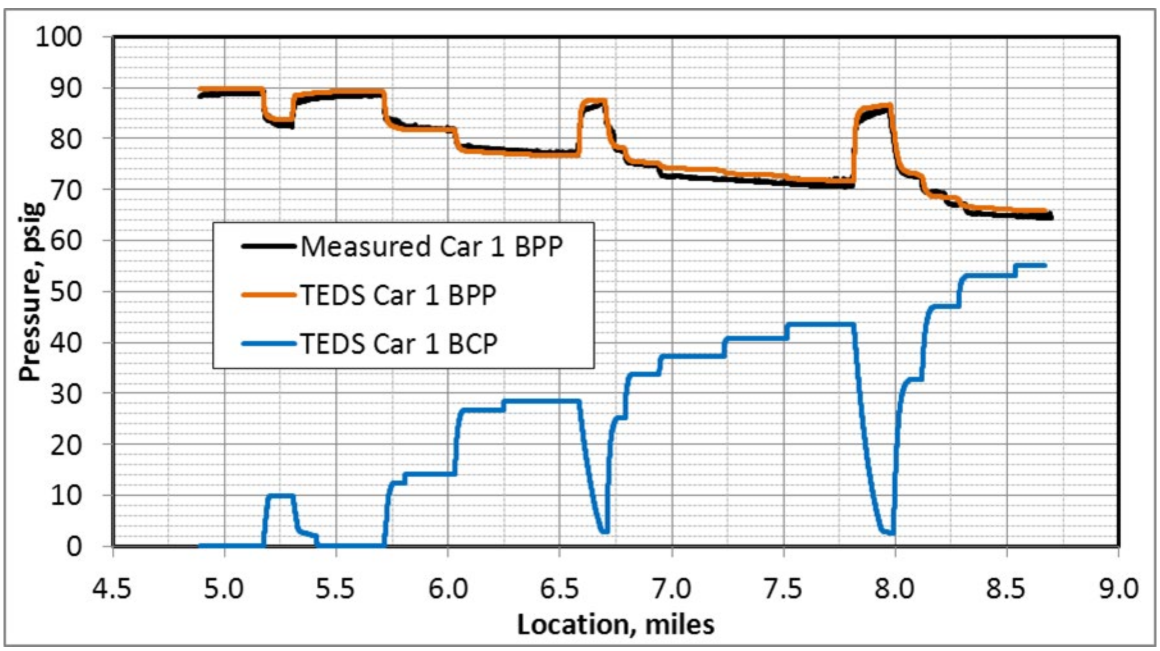

Figure 4-3. Measured and predicted brake pressures on Test Car 1 for the initial train startup and speed control test

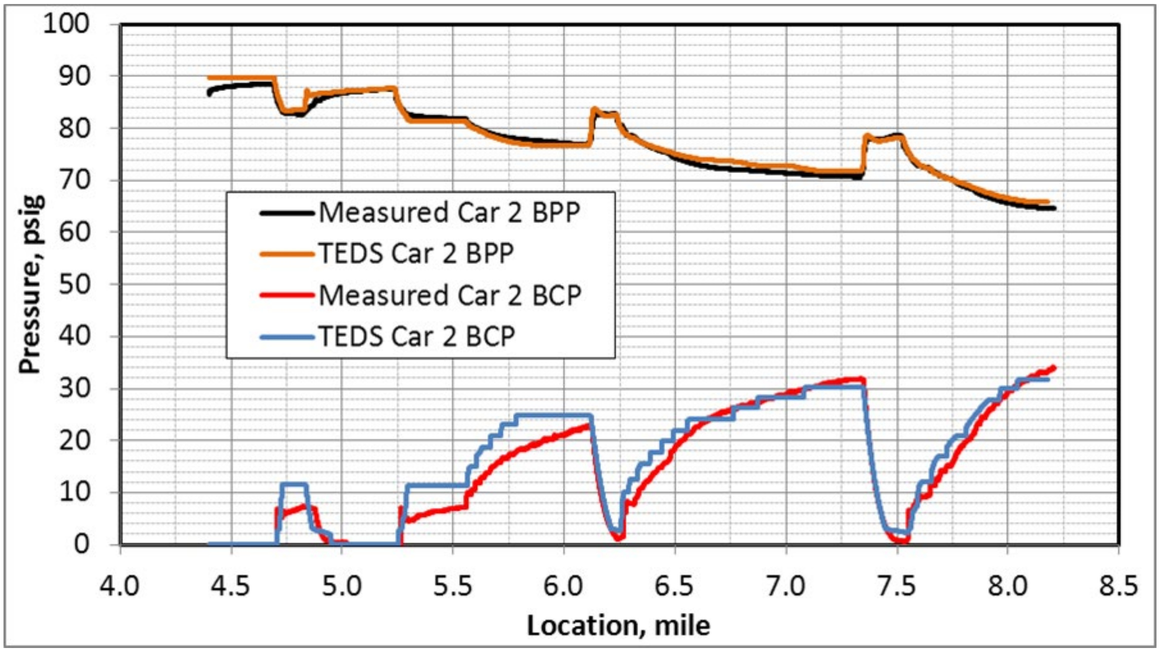

Figure 4-4. Air braking on Test Car 2 for the initial train startup and speed control test

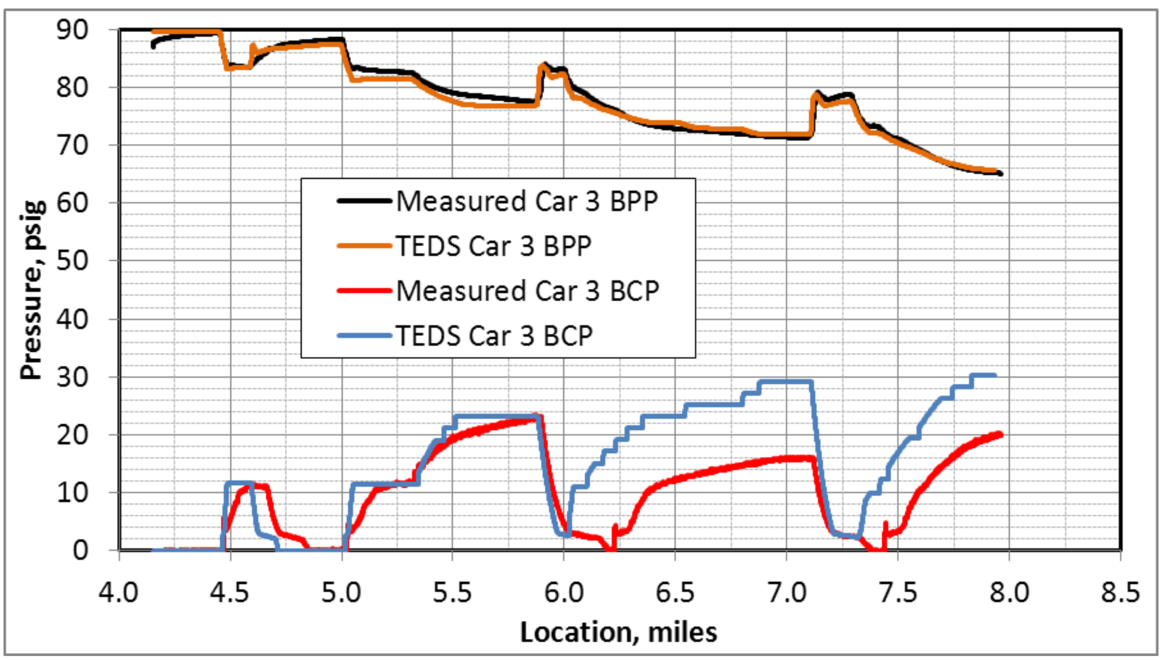

Figure 4-5. Air braking on Test Car 3 for the initial train startup and speed control test

The brake pipe pressures on Test Cars 1 and 2 are shown in Figure 4-3 and Figure 4-4 respectively. The brake pipe pressures predicted by TEDS match the measured pipe pressures accurately. For both test cars, TEDS predicted brake pipe pressures are generally within 1 psi of the measured values, and the greatest difference is no more than 2 psi.

The brake cylinder pressure predicted by TEDS on Test Car 2 accurately follows the trend of the measured brake cylinder pressure at this car, as shown in Figure 4-4. While the difference can be as high as 5 psi at times, especially during and just after minimum applications, there is accurate agreement for heavier applications.

The brake cylinder pressure predicted by TEDS for Test Car 3 accurately matches the measured brake cylinder pressure on this car for the first two applications shown in Figure 4-5. However, the subsequent applications (starting at mile 6) do not show this same level of agreement in brake cylinder pressure, despite the accurate match in the corresponding brake pipe pressures. The reason for this discrepancy is likely to be a malfunctioning control valve on Test Car 3. Specifically, the auxiliary reservoir charged more slowly than normal, perhaps due to some obstruction in the charging choke, or similar issue.

The normal recharge rate of Test Car 1 is compared to that of Test Car 3 in Figure 4-6 and Figure 4-7. The TEDS prediction for the recharge rate of the auxiliary reservoir on Test Car 1 matches the measured auxiliary reservoir recharge rate (Figure 4-6). This same recharge rate is predicted by TEDS for Test Car 3. However, the measured recharge rate on Test Car 3 is much slower (Figure 4-7). This slower recharge rate, combined with a brake application only a short time after the release, results in the brake pipe pressure at Test Car 3 not reducing below the auxiliary reservoir pressure and hence the cylinder does not apply as intended (as is typical when there is insufficient recharge). As the brake pipe pressure continues to reduce, the control valve eventually does respond by applying the brake just beyond mile 6.2.

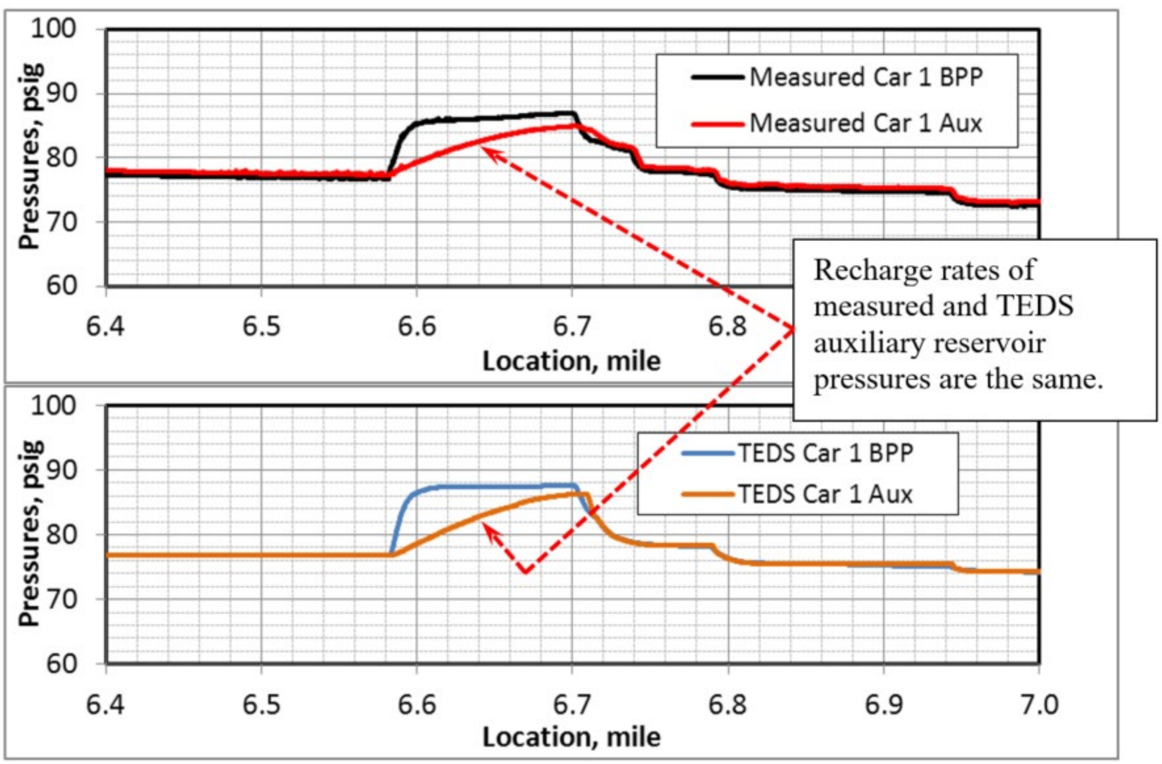

Figure 4-6. Test Car 1 pressures at release from second application and initiation of third application

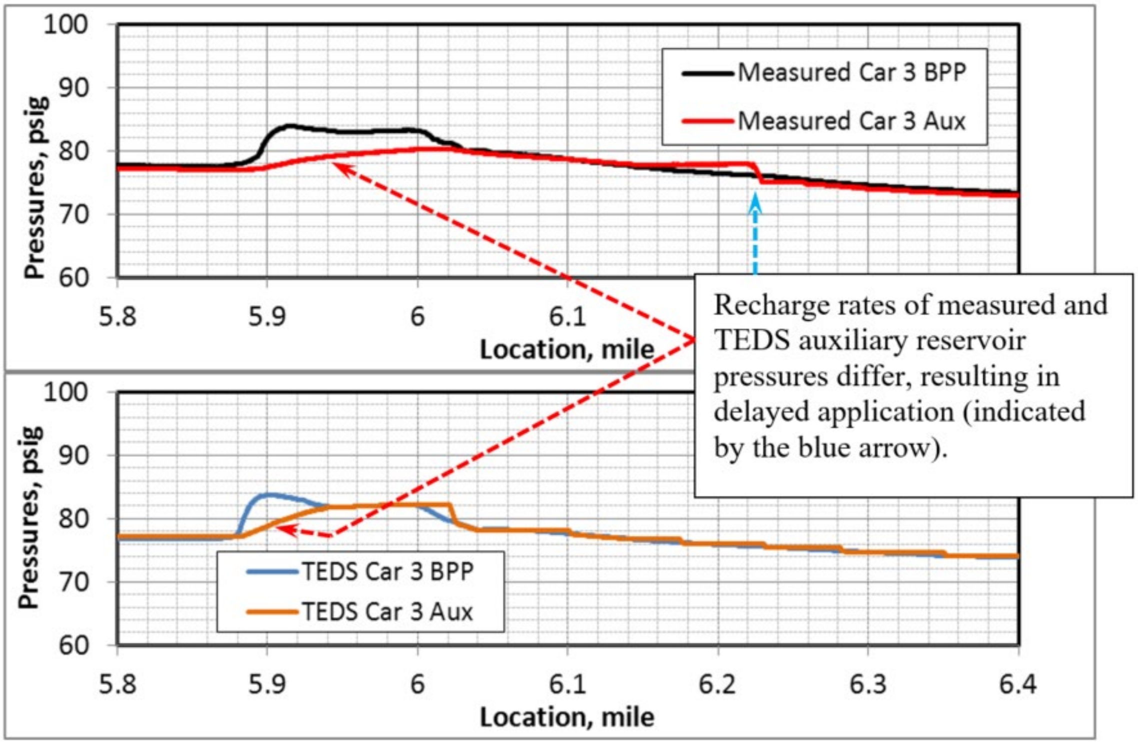

Figure 4-7. Test Car 3 pressures at release from second application and initiation of third application

4.2 Bunching and Run-out

The bunching and run-out test was conducted on the second day of testing before resuming the revenue service test. Figure 4-8 shows the notch position, locomotive brake cylinder pressure, and measured train speed. Figure 4-9 shows the train starting and ending locations on the track.

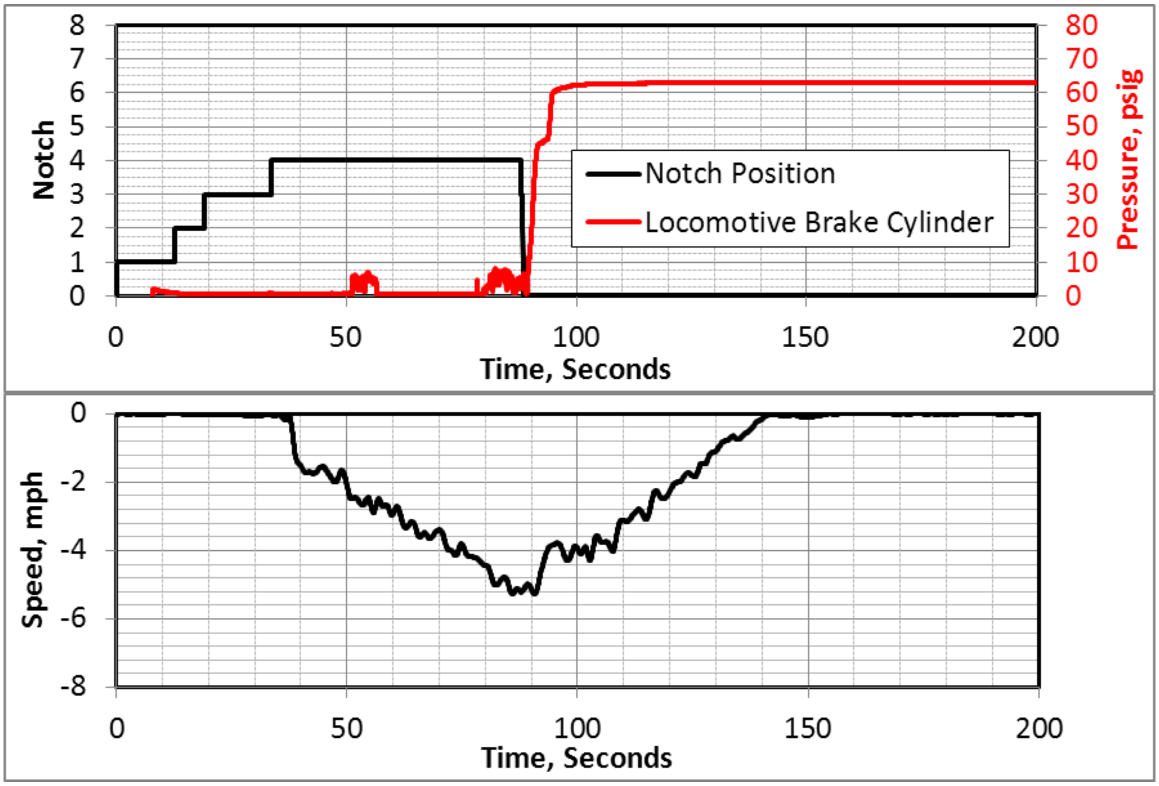

Figure 4-8. Notch position, locomotive brake cylinder pressure, and train speed for the bunching and run-out test

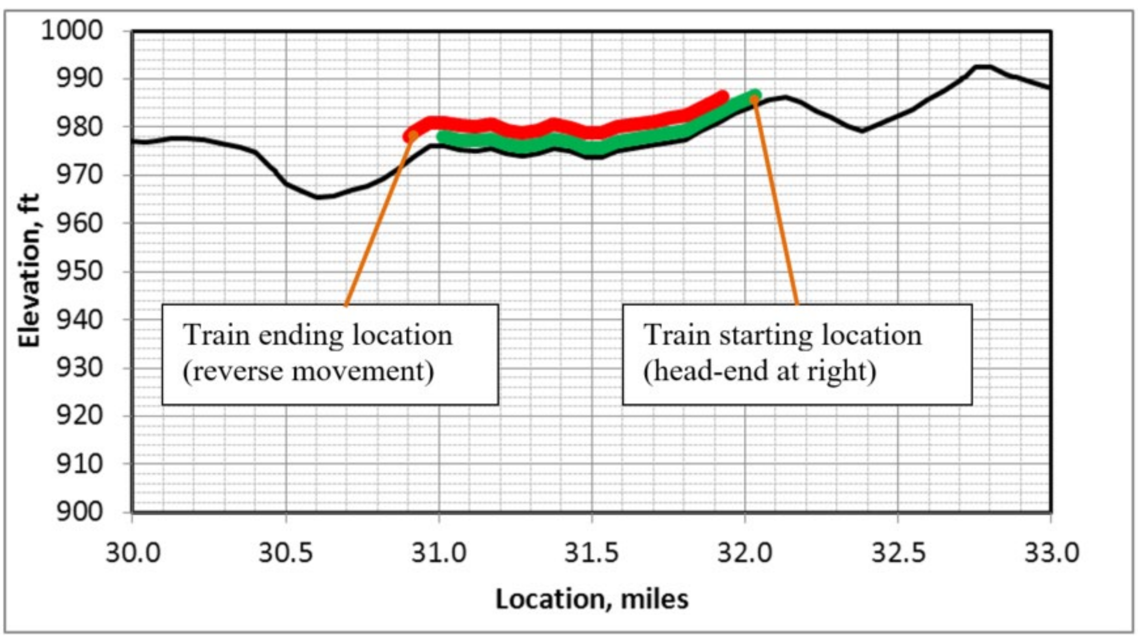

Figure 4-9. Train location on the track profile for the bunching and run-out test

The measured and predicted train speed, shown in Figure 4-10, match accurately for all but the initial part of the test. Several simulations were conducted, with varying assumptions regarding the unknown initial conditions (e.g., the state of slack between cars) in attempts to obtain a better match to the measured speed. However, accurate agreement over the initial part of the test was not achieved.

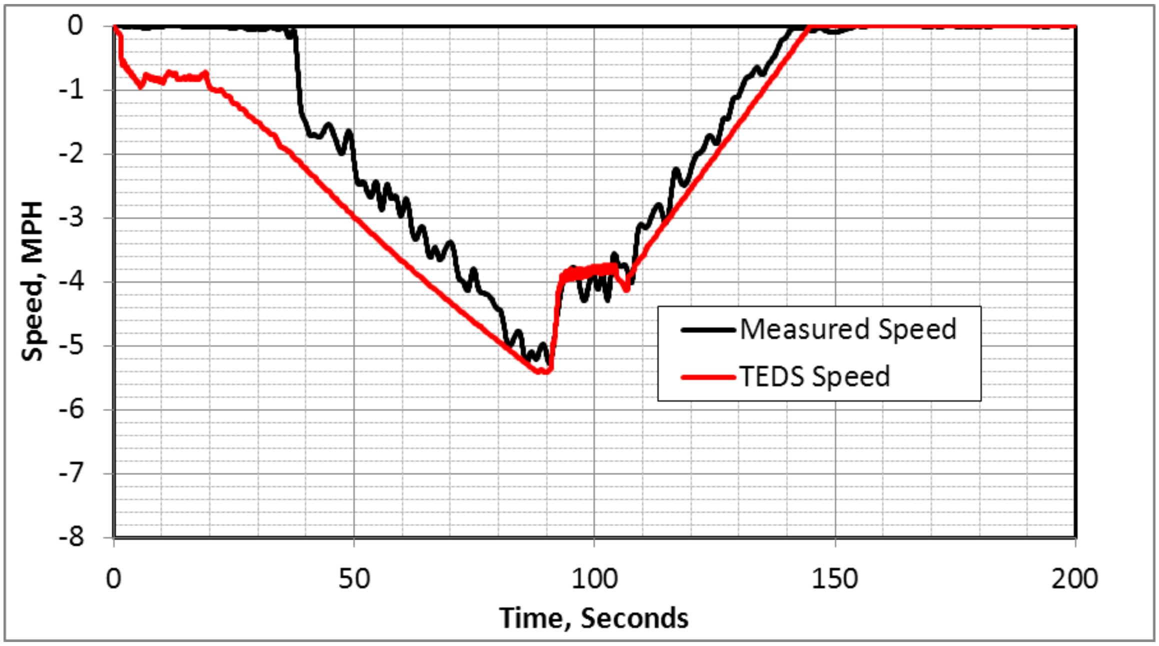

Figure 4-10. Measured and predicted train speeds for the bunching and run-out test

Although the cause of this discrepancy has not been found, the speed difference is never more than 2 mph. In addition, once the test train is reported to move, the slope of the TEDS predicted speed accurately matches that of the test train, and the difference between measured and predicted speeds remains less than 1 mph throughout the remainder of the test. This difference is well within the acceptance criterion for speed matching.

Figure 4-11 shows the measured and predicted locomotive brake cylinder pressures. The locomotive brake cylinder pressure predicted by TEDS accurately matches the measured brake cylinder pressure. Note that the lead locomotive is equipped with electronic brakes, so the maximum cylinder pressure is about 63 psi, as compared to the 72-psi typical of full independent pressure on locomotives equipped with a pneumatic 26-L brake system.

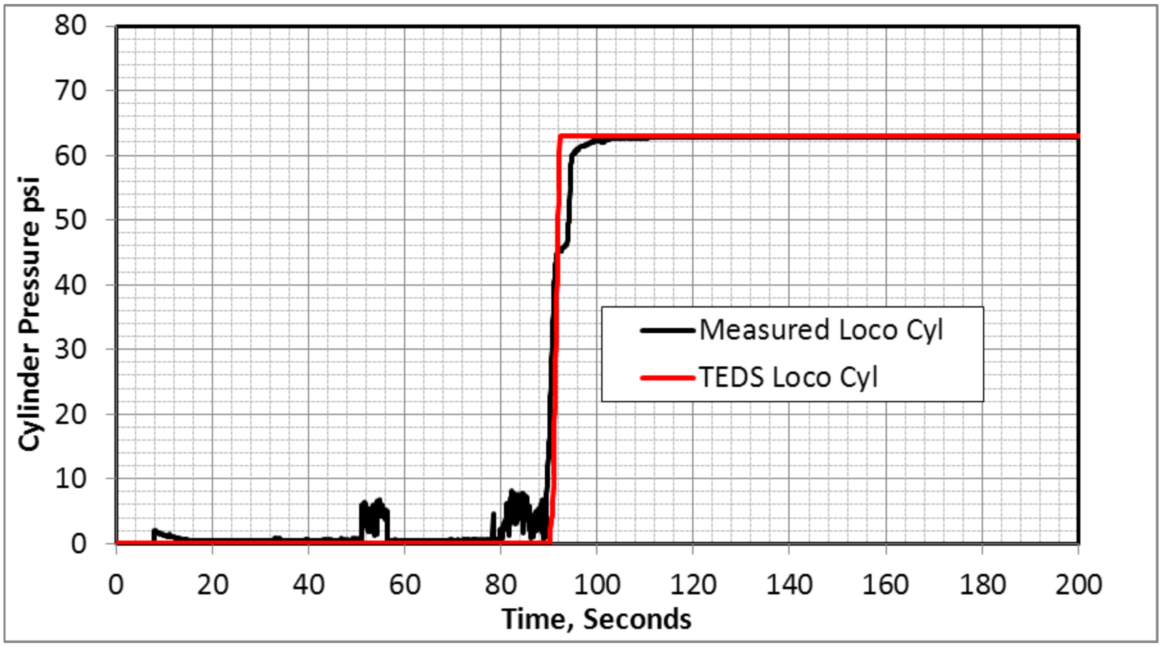

Figure 4-11. Measured and predicted locomotive brake cylinder pressures for the bunching and run-out test

Coupler forces, as measured and predicted by TEDS, for the three test cars are shown in Figure 4-12, Figure 4-13, and Figure 4-14. There is an accurate match between the TEDS predictions and measured data in each case. TEDS accurately predicted the magnitude of the peak run-out force, about 200 kips, at both Test Car 2 and Test Car 3.

The timing of the slack run-out event is accurately predicted by TEDS. At each test car, there is a sudden rise in the coupler force as that car experiences a sudden deceleration due to braking, and slack running out, from the head end. A high draft force then remains at that car until the run out reaches the end of the train, at which point the coupler force subsides to the quasi-steady state level (particular to each car) associated with the overall train deceleration. It is evident from Figure 4-13 and Figure 4-14 that TEDS accurately predicted both the onset and the termination of the run-out event (in the period between 100 and 110 seconds), as well as its magnitude of 200 kips. A detailed view of this event, for Test Car 3, is shown in Figure 4-15. The measured and predicted, start and end of the event both match to within 0.5 seconds, and the magnitude of the event differs by less than 10 percent, all of which are well within the criteria for acceptance.

These results show that the TEDS predicted coupler forces for all three cars met the validation acceptance criteria set out in Section 1.3.

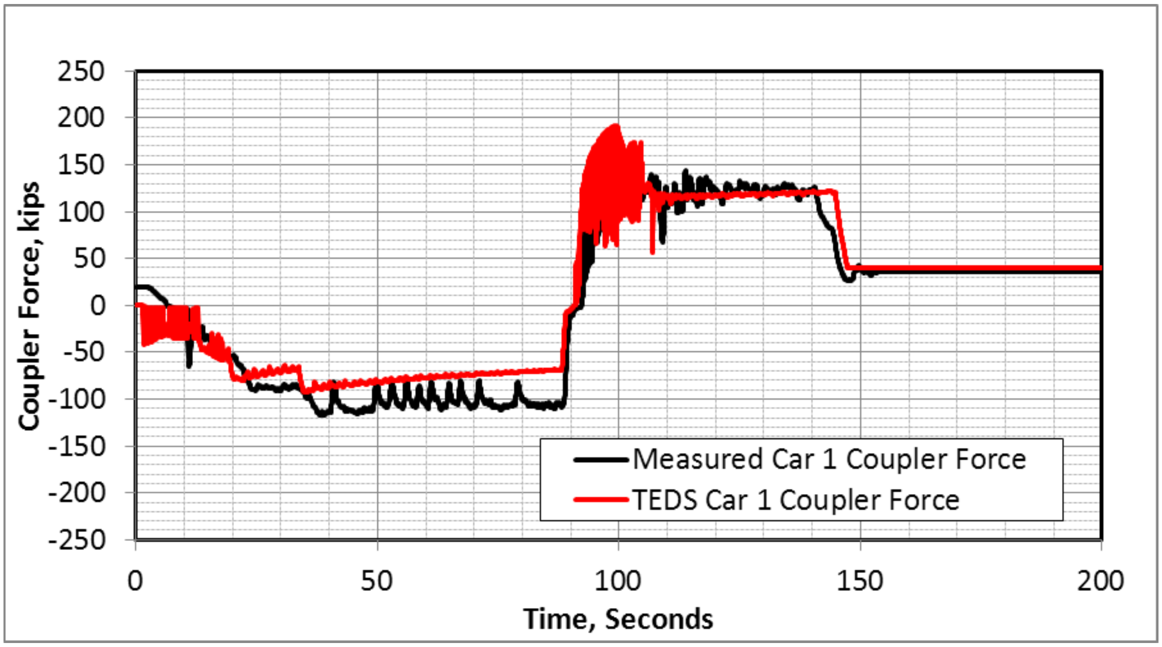

Figure 4-12. Measured and predicted Test Car 1 coupler forces for the bunching and run-out test

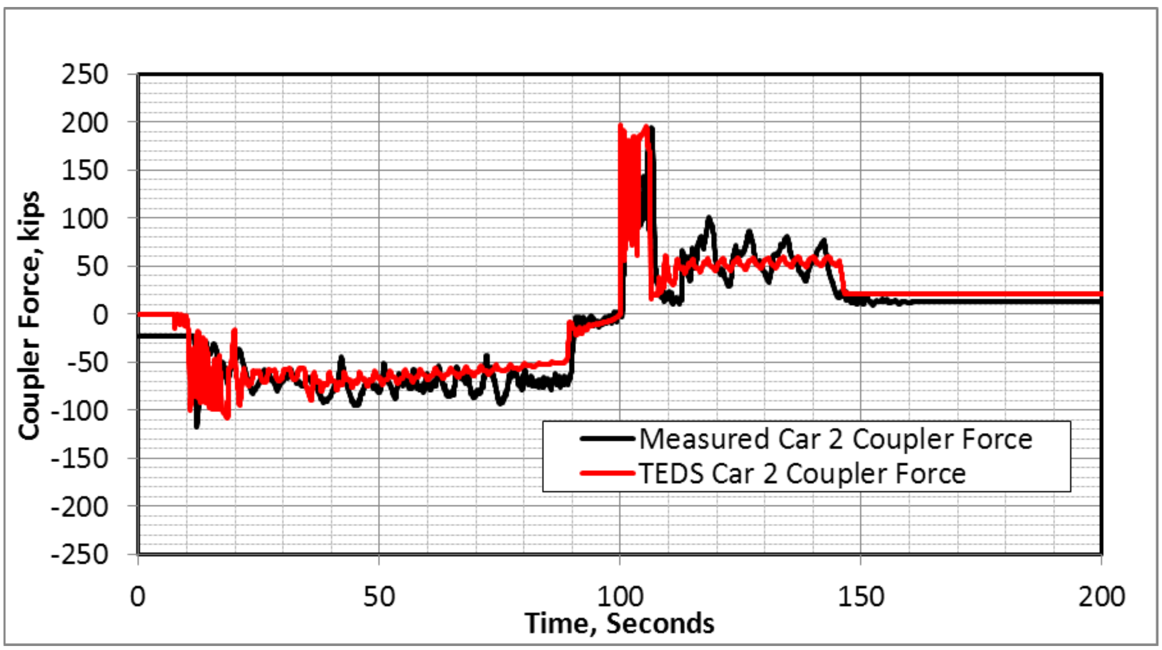

Figure 4-13. Measured and predicted Test Car 2 coupler forces for the bunching and run-out test

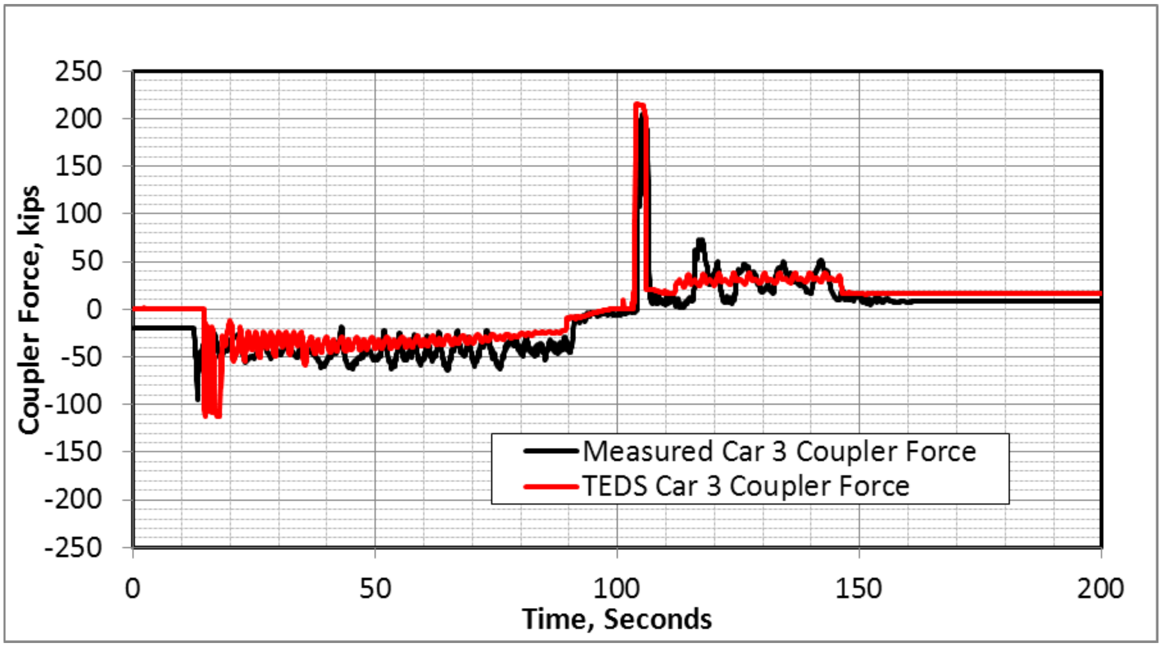

Figure 4-14. Measured and predicted Test Car 3 coupler forces for the bunching and run-out test

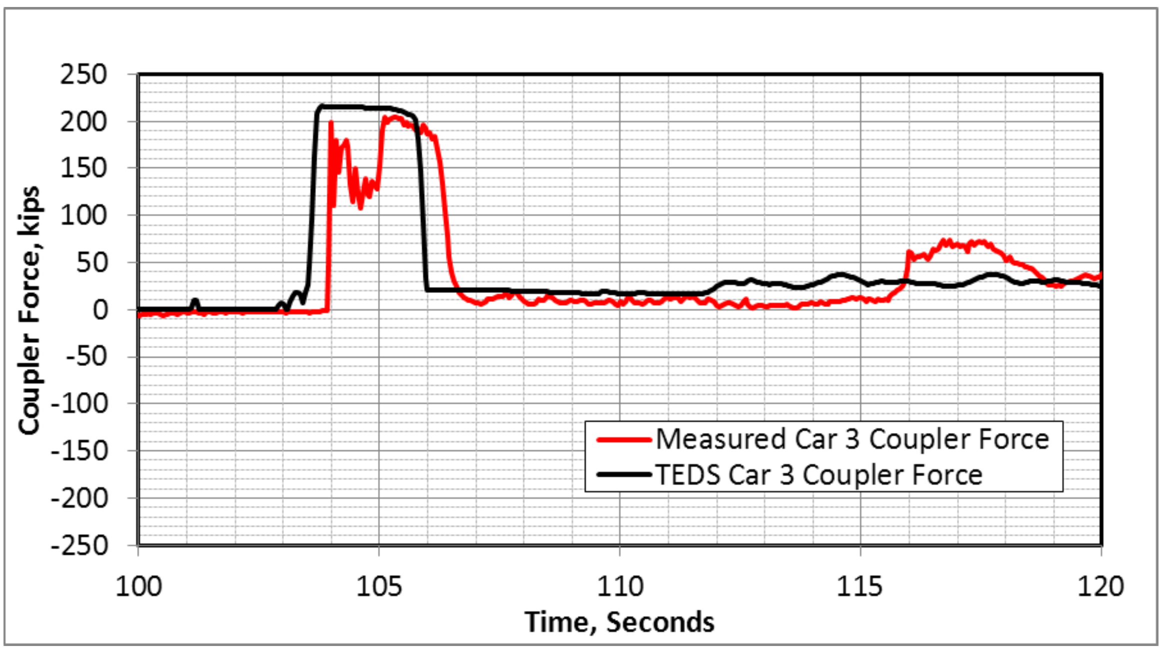

Figure 4-15. Expansion of Test Car 3 coupler forces in the run-out event region

4.3 Slack Action with Run-in

The slack action with run-in test was conducted after the bunching and run-out test. The measured locomotive brake cylinder pressure, throttle position, elevation profile, and train speed are shown in Figure 4-16. The location of the train on the track profile, at various points during this movement, is shown in Figure 4-17.

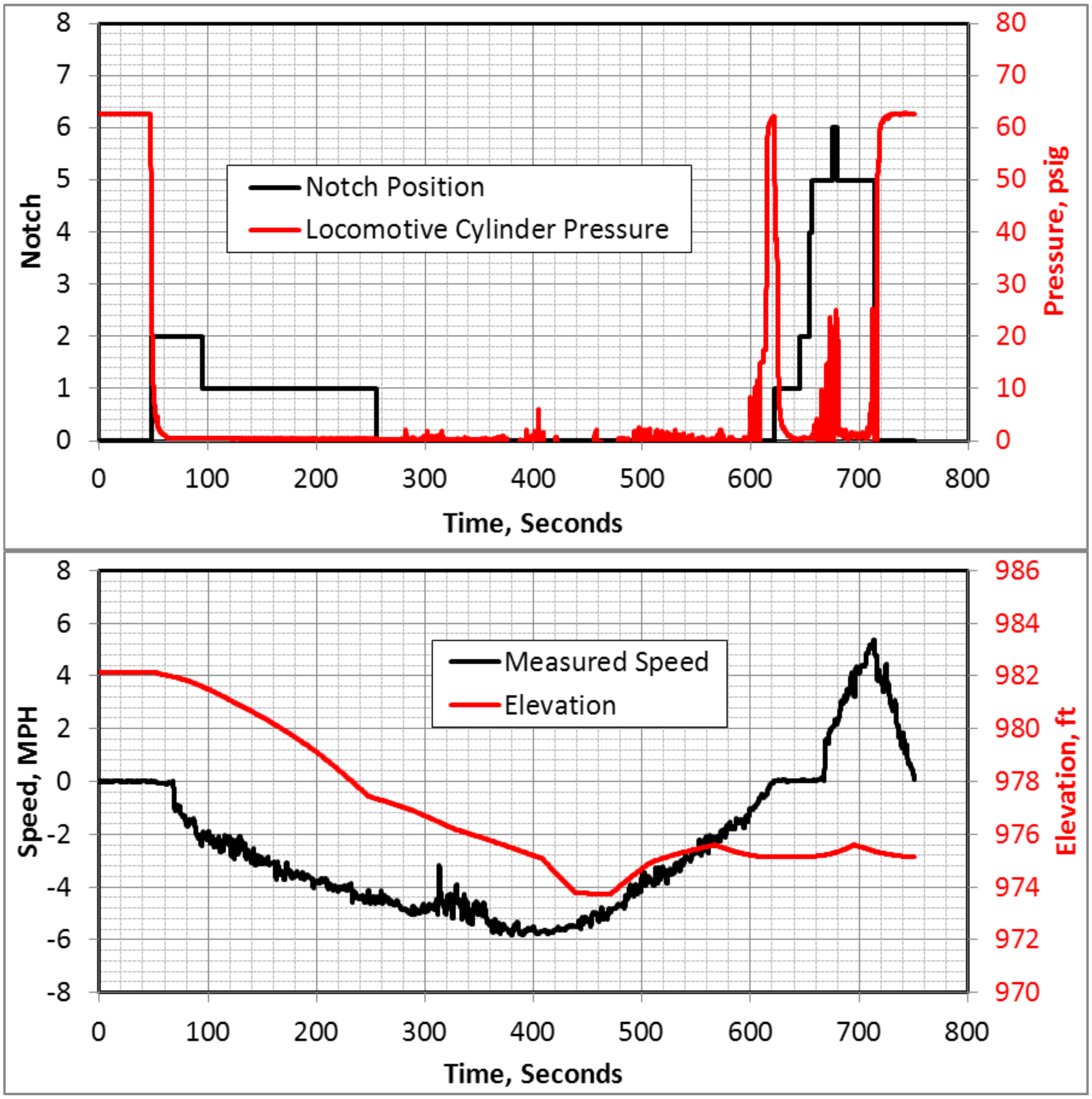

Figure 4-16. Throttle position, locomotive brake cylinder pressure, train speed and elevation profile for the slack action with run-in test

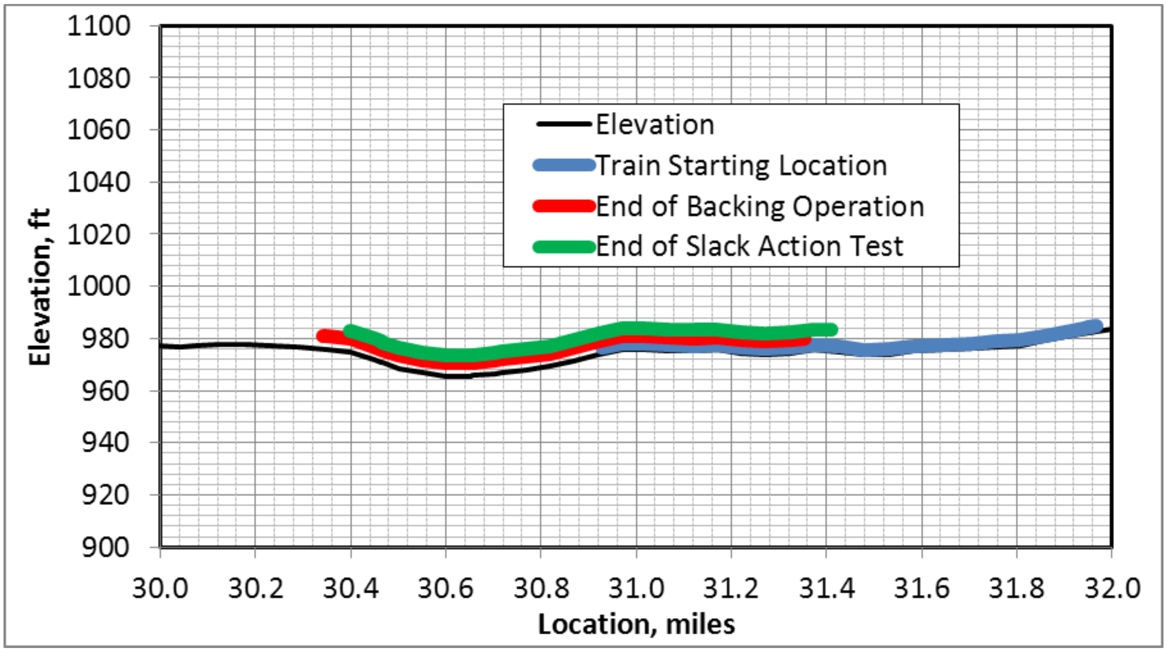

Figure 4-17. Train location on the track profile for the slack action with run-in test

The TEDS speed prediction is compared to the measured speed in Figure 4-18. The speed profile predicted by TEDS agrees with the measured speed profile. The maximum speed difference is approximately 1 mph, and most of the time it is much less. This is well within the acceptance criterion for speed defined in Section 1.3.

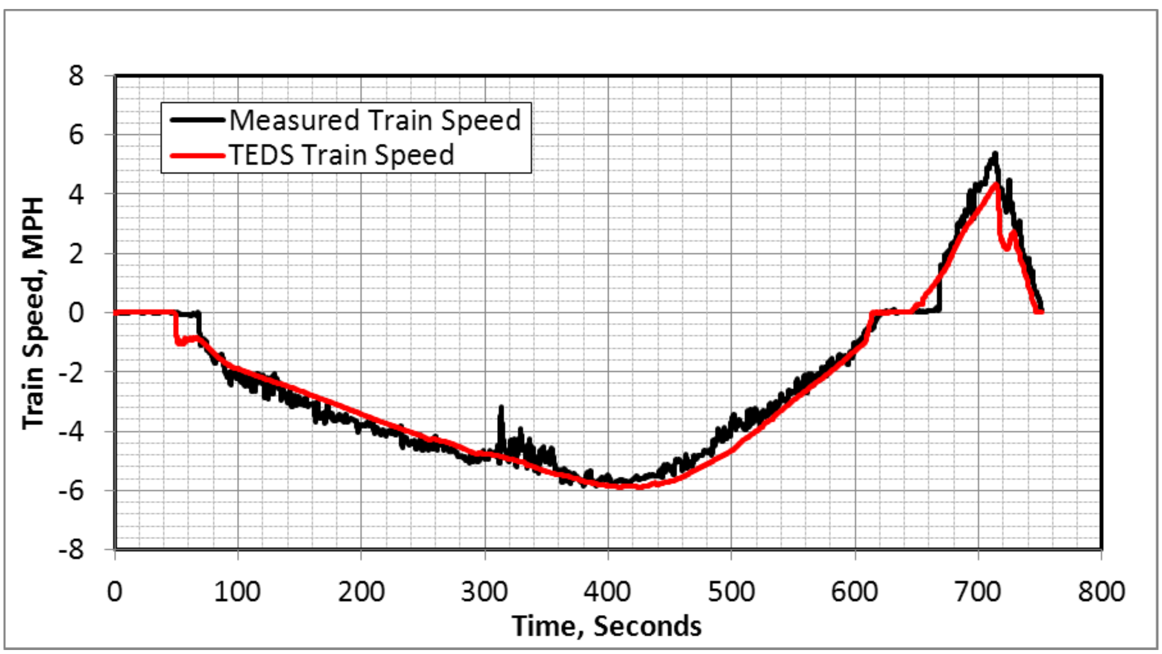

Figure 4-18. Measured and predicted train speeds for the slack action with run-in test

The measured and predicted locomotive brake cylinder pressures are compared in Figure 4-19. The upward spikes appearing in this test data are due to instrumentation noise and therefore were not simulated. TEDS accurately predicted the locomotive brake cylinder pressure. There is a nearly perfect match in both build up and release rate, as well as full cylinder pressure level.

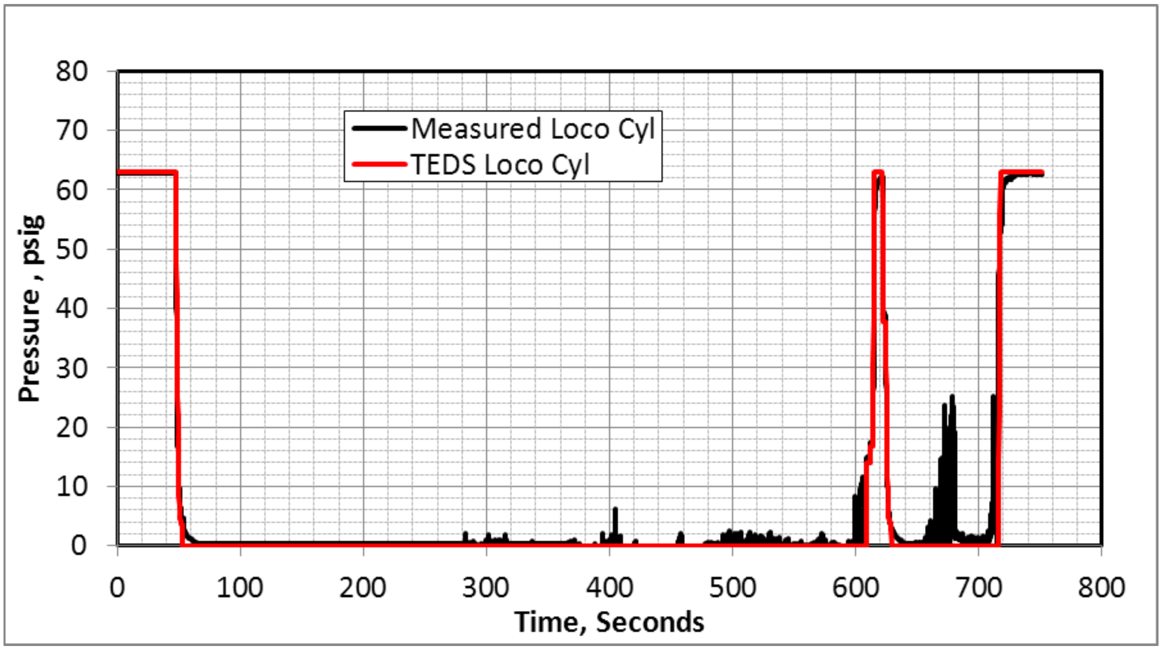

Figure 4-19. Measured and predicted locomotive brake cylinder pressures for the slack action with run-in test

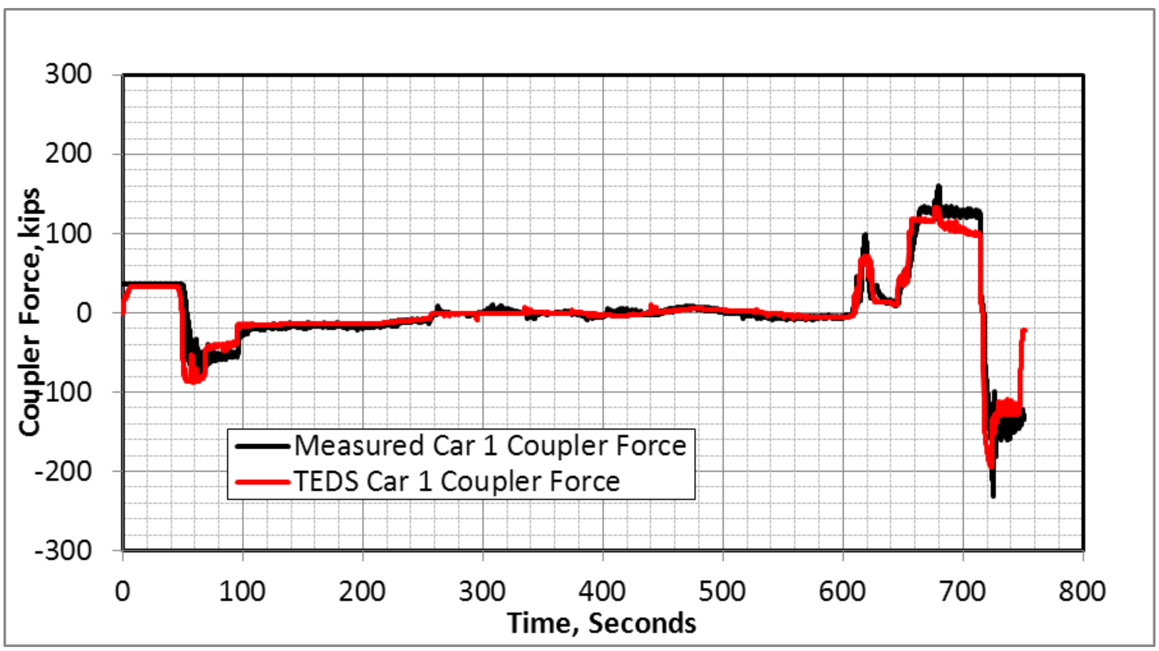

Figure 4-20. Measured and predicted coupler forces on Test Car 1 for the slack action with run-in test

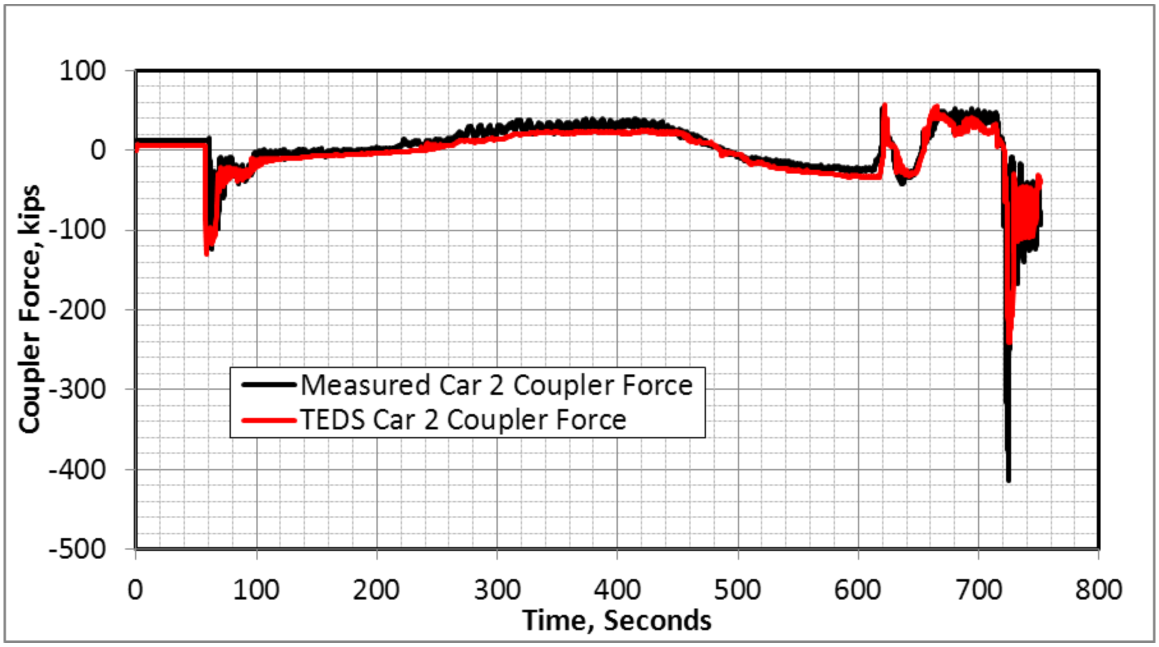

Figure 4-21. Measured and predicted coupler forces on Test Car 2 for the slack action with run-in test

The comparison of the measured and predicted coupler forces on the three test cars is shown in Figure 4-20, Figure 4-21, and Figure 4-22. In all three cases, the TEDS predictions are accurate. The run-in forces between 50 and 100 seconds are due to the reverse movement of the locomotives picking up and bunching the cars that had been stretched out by the previous run-out maneuver. The run-out forces just after 600 seconds correspond to the forward movement with the locomotives now picking up and stretching the previously bunched cars. The sustained draft forces between 650 and 710 seconds—high at the front of the train and lower further back in the train—correspond to the increased TE from quickly increasing the throttle to a relatively high notch. The final run-in event, at about 725 seconds, occurs when the sudden reduction of throttle and full application of independent brake causes the cars to run in to the locomotive consist.

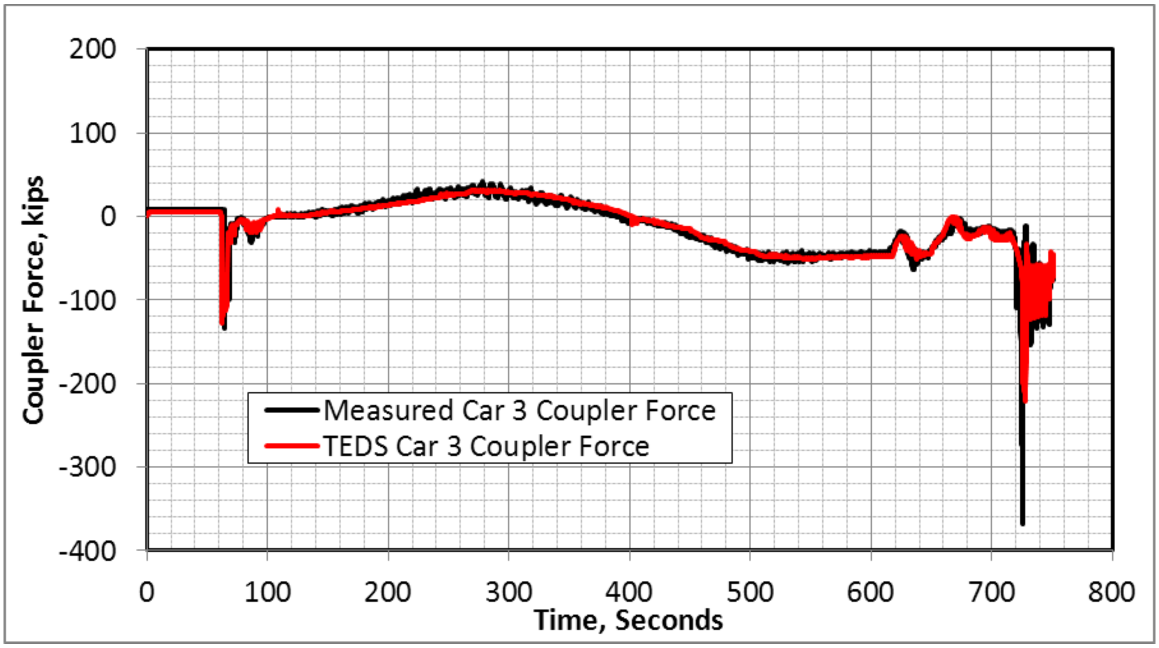

Figure 4-22. Measured and predicted coupler forces on Test Car 3 for slack action with run-in test

The timing of these slack action events at each test car is accurately predicted by TEDS. Predicted coupler force magnitudes are close to the measured values, although TEDS tends to under predict the large run-in forces near the end of the scenario at 725 seconds. This is attributed to the phenomenon of friction draft gear to show a spike in the closing force when the relative motion between the impacting bodies is arrested. The size of this spike is dependent on the relative speed at which the bodies collide and the energy is absorbed. The TEDS model is not designed to capture this spike, which has a very short duration and accounts for a small fraction of the energy absorbed. Examination of the shape of this run-in spike reveals that, although the TEDS predicted maximum magnitude is lower than that measured, the TEDS force remains at a high level longer than the measured response. Thus, there is close agreement between the measured and TEDS predicted impulse (integral of force over time), which is directly related to the exchange of momentum between cars. In addition, the test cars are relatively old and their draft gear components may have degraded over time. Worn parts could cause the gear to go solid (generating a high force) sooner than would be the case with the modeled (ideal) characteristics. Hence, although some predicted peak force levels can be as much as 40 percent below the measured value, the overall response to this event is considered acceptable.

4.4 Air Brake Applications, Including Emergency

The air brake testing was conducted at the beginning of the second day, before the bunching and slack action tests and before starting the final revenue service test. The train was not in motion during the brake application tests. Several applications and releases were made as shown in Figure 4-23. The reapplication shortly after the release between 1,000 and 1,500 seconds was intended to measure the effect of insufficient recharge.

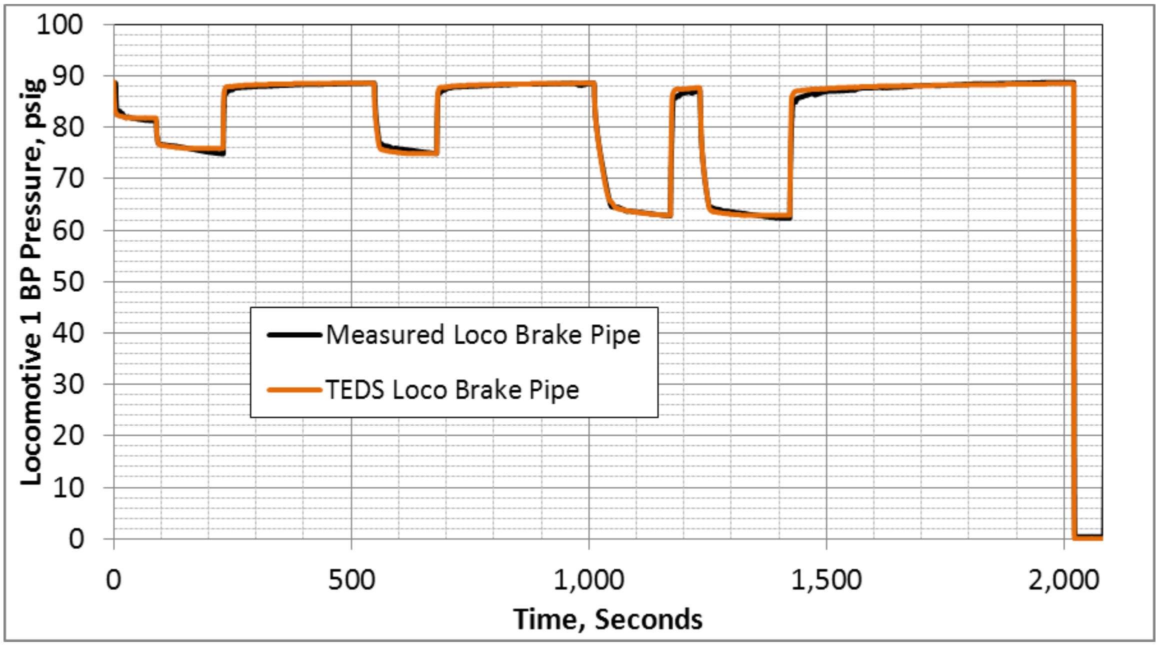

Figure 4-23. Measured and predicted locomotive brake pipe pressures for the braking test

Figure 4-24 compares the brake pipe pressure predicted by TEDS to the measured brake pipe pressure on Test Car 1. For reference, predicted brake cylinder pressure on Test Car 1 is also shown on this plot—cylinder pressure data was not obtained for Test Car 1. Similarly, Figure 4-25 compares the measured and predicted auxiliary reservoir pressures on Test Car 1, with the predicted brake cylinder pressure shown for reference.

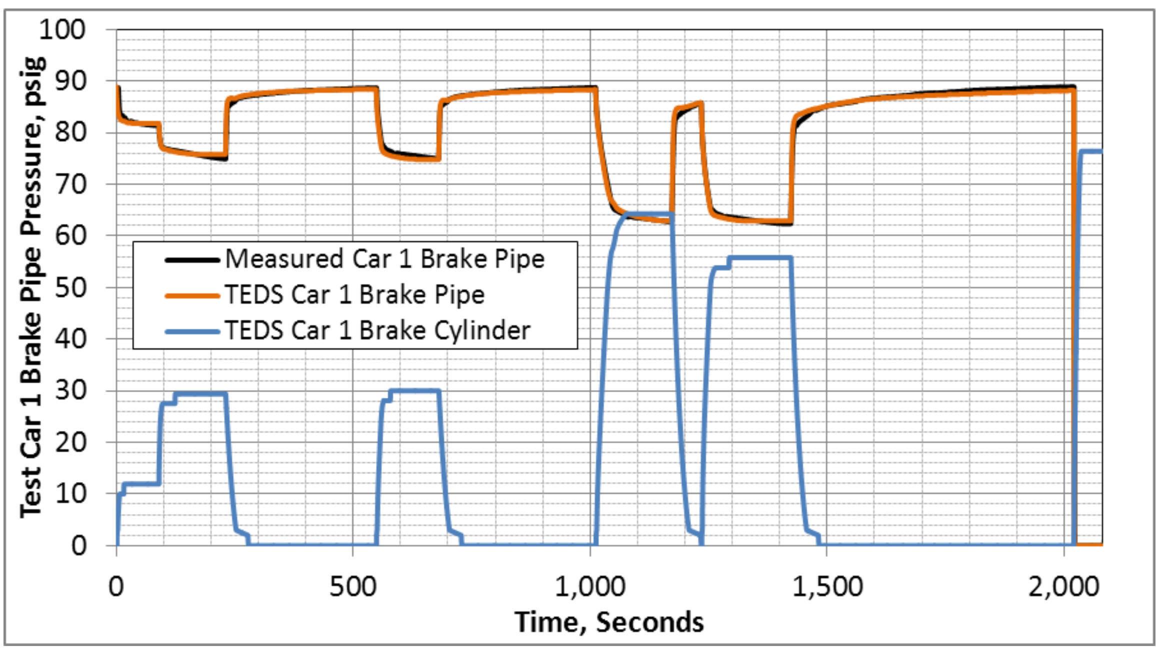

Figure 4-24. Measured and predicted brake pipe pressures on Test Car 1 for the braking test

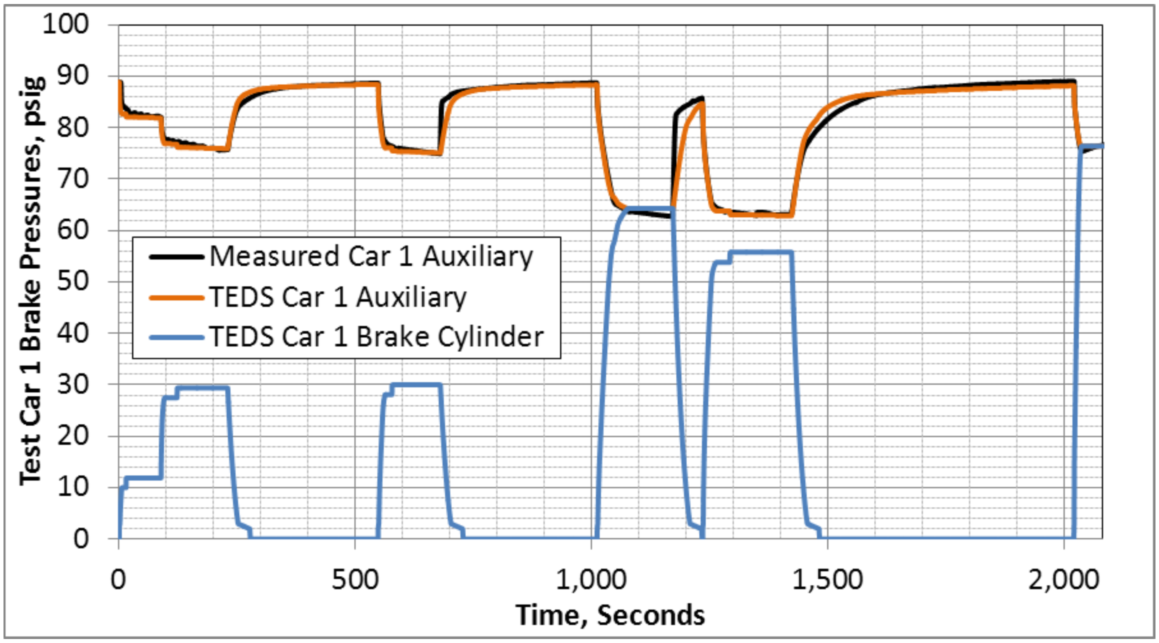

Figure 4-25. Measured and predicted auxiliary reservoir pressures on Test Car 1 for the braking test

Predicted brake pipe and auxiliary reservoir pressures accurately match their measured values. Differences of as much as 3 to 5 psi occasionally exist for a short time during a transient pressure change, but the agreement is generally within 1 psi. The brake system match on the locomotive and Test Car 1 is well within the acceptance criterion.

Comparison of the brake pipe and brake cylinder pressures on Test Car 2 is shown in Figure 4-26, and comparison of the pressures on Test Car 3 is shown in Figure 4-27. Predicted and measured brake pipe pressures at these test cars are accurate, with any differences within the acceptance criterion.

The brake cylinder pressure on Test Car 2 appears erratic. Predicted and measured brake cylinder pressures match accurately for the second and third applications. However, for the first brake application TEDS predicts too high and for the fourth application TEDS predicts too low. These differences are in the range of 6 to 8 psi. A large part of this discrepancy may be due to a malfunctioning control valve, given that the variance is not in a uniform direction.

Predicted brake cylinder pressure at Test Car 3 matches the measured pressure after increasing the piston travel in this simulated car by 12 percent above the nominal value, which is a reasonable assumption given the age of the brake system (ABD control valve) and condition of this car. With this adjustment, brake cylinder pressure at Test Car 3 matches the measured value within 3 psi or less, which is well within the acceptance criterion.

In addition, TEDS accurately predicts the effect of insufficient recharge on the quickly-made reapplication at about 1,200 seconds, as shown at Test Car 1 by the lower brake cylinder pressure on the second full service application (i.e., 56 psi on the second application, as opposed to 64 psi on the first). The effects of insufficient recharge are also accurately predicted on Test Cars 2 and 3. Not only does the second full service application produce lower cylinder pressures than the first application, but the cylinder pressure is progressively lower toward the rear of the train, as expected, since the rear of the train recharges more slowly than the front.

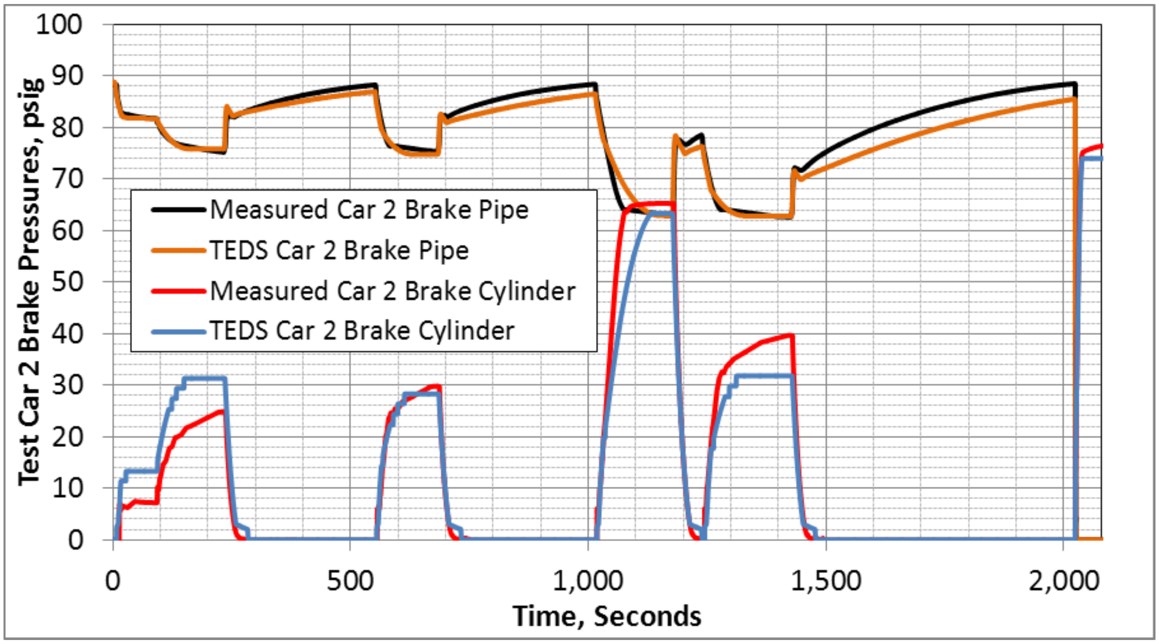

Figure 4-26. Measured and predicted brake pipe and cylinder pressures on Test Car 2 for the braking test

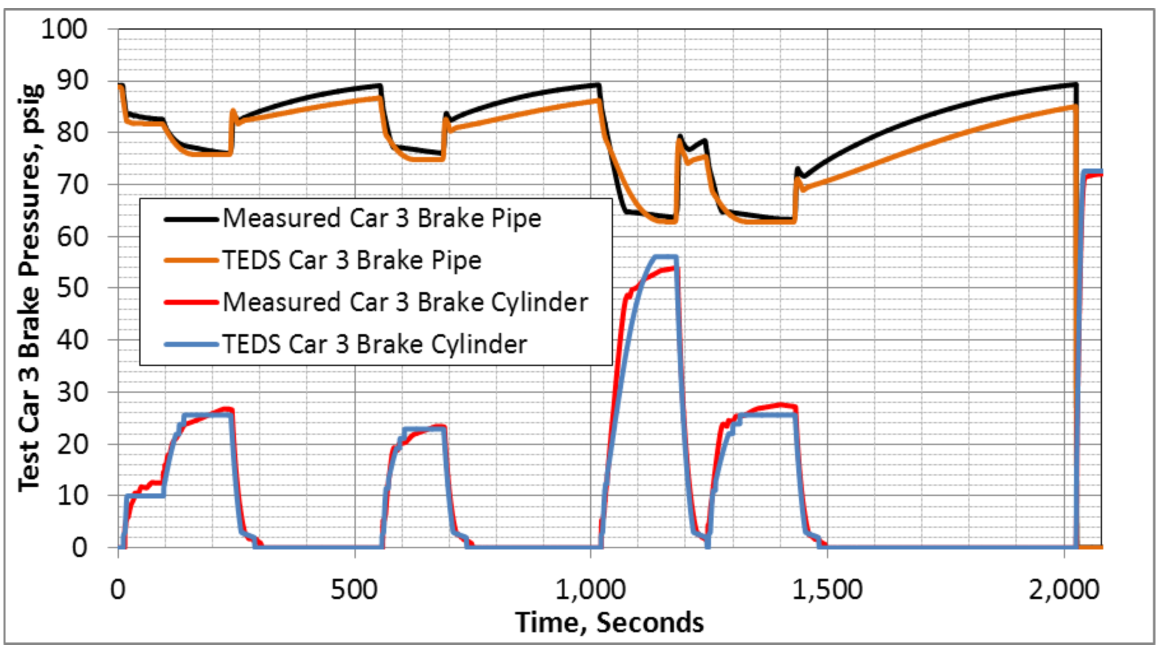

Figure 4-27. Measured and predicted brake pipe and cylinder pressures on Test Car 3 for the braking test

5 Conclusion

A revenue service validation test was conducted under the first-part of this effort for TEDS on a unit train of 84 loaded cars pulled by 3 locomotives. The test took place from June 12, 2013, through June 11, 2016, covering typical major train operating scenarios, such as starting a train from stop and maintaining speed through throttle manipulation and use of automatic air brakes.

Additionally, to establish the TEDS ability to represent slack action, bunching and run-out tests were also conducted. Air brake applications, including emergency, were made with the train standing.

Instrumentation was applied to collect throttle position, train speed, locomotive power, brake system response and coupler forces in the test train, and operational data was collected for input to post-test TEDS simulations.

Validation acceptance criteria were defined for brake response (e.g., brake pipe, brake cylinder pressure), train speed, and coupler force to compare TEDS predictions with the measured test data.

Comparisons between measured data and simulation results show TEDS speed predictions are accurate. For a track segment of 3.5 miles with six major throttle changes and four air brake applications, the speed predicted by TEDS rarely differed by more than 1 mph from that measured during the test. The maximum difference, of about 2.5 mph, occurred during a transient slack adjustment resulting from the initial brake application.

For the bunching and run-out tests, coupler forces measured on the three instrumented cars varied from 120 kips in buff to 220 kips in draft. TEDS accurately predicted the magnitude of the peak run-out force on both Test Car 2 and Test Car 3 at approximately 200 kips, which was within 10 percent of the measured value. TEDS also accurately predicted the onset and the termination of the run-out event. The measured and predicted, start and end of the event both matched to within 0.5 seconds. These results show that TEDS predicted coupler forces for all three cars met the validation acceptance criteria.

Slack action and run-in tests were conducted with recordings of throttle position, train speed, and coupler forces. The coupler forces in the test varied from 100 to 400 kips in buff and up to a maximum of 150 kips in draft. On all three cars, TEDS predicted the steady state coupler force magnitudes to within the validation acceptance criteria of ±20% of the measured values. For example, TEDS predicted 130 kips for the maximum draft force of 150 kips measured on Test Car 1.

The timing of the slack action events at each test car were accurately predicted by TEDS. Predicted coupler force magnitudes were close to the measured values, although TEDS tended to under predict the short duration run-in forces associated with the initial impact of a large run-in event. The TEDS draft gear model is not designed to capture this spike, which has a very short duration and accounts for a small fraction of the energy absorbed. Hence, although some predicted peak force levels were as much as 40 percent below the measured value, the overall response to this event is considered acceptable.

The air brake tests included a minimum service, partial and full service, and emergency applications. The brake pipe and brake cylinder pressures on three cars were measured and compared with TEDS predictions.

Although the maximum difference between the measured and predicted pressure for brake pipe was occasionally as much as 3 to 5 psi for a short time during a transient pressure change, the agreement was generally within 1 psi, which is well within the acceptance criterion.

There was general agreement between the predicted and measured values of brake pipe and brake cylinder pressure on each of the three cars, with any differences within the acceptance criterion of ±5 psi during transients. The steady-state values were in closer agreement.

In addition, TEDS also accurately predicted the effect of insufficient recharge, resulting from a brake application made shortly after a release, on the brake system pressures.

Overall, the unit train validation tests were planned and executed successfully. Simulation of the unit train tests clearly established the capability of TEDS to replicate field events within the validation acceptance criteria.

6 References

1 Federal Railroad Administration, "Validation of the Train Energy and Dynamics Simulator (TEDS)," Technical Report No. DOT/FRA/ORD-15/01, Washington, DC: U.S. Department of Transportation, January 2015.

2 Andersen, D. R., Booth, G. F., Vithani, A. R., Singh, S. P., Prabhakaran, A., Stewart, M. F., and Punwani, S. K., “Train Energy and Dynamics Simulator (TEDS) – A State-of-the-Art Longitudinal Train Dynamics Simulator,” Proceedings of *the ASME 2012 Rail Transportation Division Fall Technical Conference*, October 16–18, 2012.

3 Stewart, M. F., Punwani, S. K., Andersen, D. R., Booth, G. F., Singh, S. P., and Prabhakaran, A., “Simulation of Longitudinal Train Dynamics: Case Studies Using the Train Energy and Dynamics Simulator (TEDS),” Proceedings of *the ASME 2015 Joint Rail Conference*, March 2015.

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
AAR	American Association of Railroads
ASME	American Society of Mechanical Engineers
cfm	Cubic Feet per Minute
DC	Direct Current
ECP	Electronically Controlled Pneumatic
FRA	Federal Railroad Administration
GPS	Global Positioning Satellite
INRR	Indiana Northeastern Railroad
kips	Kilo Pounds
PTC	Positive Train Control
SA	Sharma & Associates, Inc.
TE	Tractive Effort
TEDS	Train Energy and Dynamics Simulator