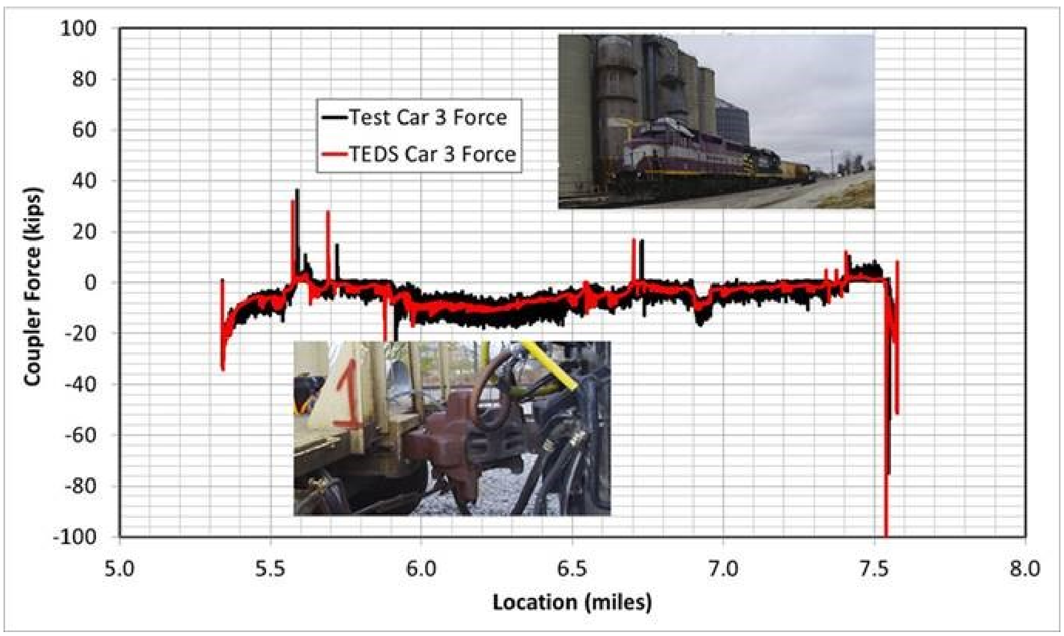
U.S. Department of Transportation

Federal Railroad Administration

Train Energy and Dynamics Simulator (TEDS) Revenue Service Validation: Volume II Mixed Manifest Train with Distributed Power

Office of Research, Development and Technology
Washington, DC 20590



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13. ABSTRACT (Maximum 200 words)

From June 12, 2013, to July 31, 2017, the Federal Railroad Administration funded the development of the Train Energy and Dynamics Simulator (TEDS) software 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 TEDS predictions using data collected from a revenue service mixed manifest train. The test train had two locomotives at the head end and a remote helper at the rear end of the train. The remote throttle was operated in sync with the head end. Standing train air brake tests for full service and emergency applications were conducted for the distributed power configuration.

Like the validation effort for the unit train completed in 2016, 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 mph of the measured speed. Significant coupler forces, higher than 100 kips, are within ± 20% and brake system pressures are within ±5 psi of measured data. These results clearly establish the ability of TEDS to accurately replicate field events and complete the TEDS validation effort.

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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

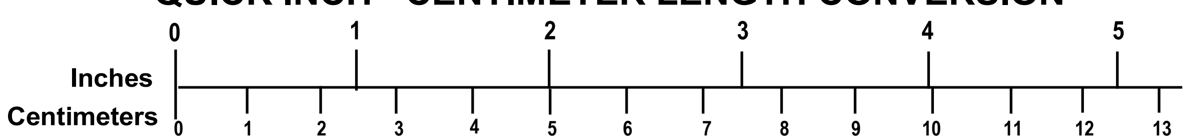
VOLUME (APPROXIMATE)

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)

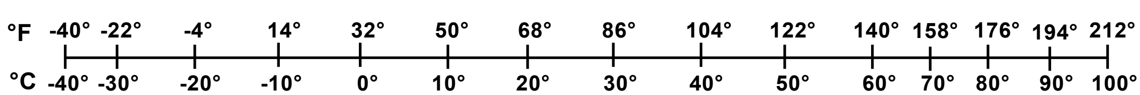
TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



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. The work for this research was conducted from June 12, 2013, to July 31, 2017.

TEDS can be used to validate a level of confidence in predicted results generally consisting 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 mixed train of 57 cars and three locomotives. Two locomotives were at the head-end and one was at the end of the train allowing data to be collected to validate TEDS in a distributed power configuration. The tests covered typical train operating scenarios, such as starting a train from a stop and maintaining speed through throttle manipulation and use of automatic air brakes including a stop. Additional air brake tests, including emergency application, were conducted with the train standing to characterize the air brake system behavior under distributed power mode.

Instrumentation and the data collection system measured and recorded throttle position, train speed, locomotive power—through traction motor #2 current and voltage—brake system response and coupler forces in the test train. Relevant track and train data was also collected for input to TEDS simulations.

For validation purposes, the following acceptance criteria were used:

- Train speed, within ±2 mph
- Transient coupler force amplitude, within ±20%
- Steady state brake pipe and brake cylinder pressure, within ±5 psi

As shown in the coming sections, speeds predicted by TEDS were found to be accurate and met the stated criterion. For a track segment of 2.23 miles with 10 major throttle changes and 2 air brake applications, the speed predicted by TEDS did not differ by more than 1 mph from the measured speed during the test.

The air brake application tests included full service and emergency, with the remote locomotive acting as a second brake pipe controller. The brake pipe and brake cylinder pressures on three cars were measured and compared with the results predicted by TEDS. This car was selected since it was the furthest from the lead and remote locomotives.

The predicted and measured values of brake pipe and brake cylinder pressure on the other two test cars agreed well. The differences for all three cars were within the validation acceptance criterion during transients. The steady-state values were within closer agreement.

A simulation-only comparison of air brake behavior was made between a train with distributed power and one with head-end power only. Distributed air brake control was compared with head-end only air brake control. This comparison showed that TEDS can clearly simulate all these scenarios.

An earlier validation effort for a unit train with head-end power showed TEDS met the validation criteria for various train operation events. This report shows TEDS has the same level of predictive capabilities for a distributed power configuration.

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

1. Introduction

From June 12, 2013, to July 31, 2017, Sharma & Associates Inc. (SA) developed the Train Energy and Dynamics Simulator (TEDS) under contract from the Federal Railroad Administration (FRA). TEDS is simulation software used to study train operation safety and performance as affected by equipment, train makeup, train handling, track conditions, operating practices, and environmental conditions.

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

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

TEDS can be used for scenarios consisting of a wide variety of freight locomotives and cars, track layouts, posted track speeds, train handling and operating conditions.

1.1 Background

To establish the level of confidence in the predicted results of simulation software, it is imperative that the software be validated. Validation generally consists of comparing software simulated results with data measured under realistic field conditions for enough scenarios to gain sufficient confidence in the predictions.

This report documents the planning and execution of the second of a series of two revenue service train tests for validating TEDS. The objective is to quantify the accuracy of TEDS predictions through comparisons of measured data with simulation results from TEDS.

The first validation effort based on revenue service testing on a grain unit train was completed in February 2016 [1].

The second validation test (i.e., the subject of this report), performed in December 2016, focused on the operation of a mixed manifest train with distributed power. In addition to head-end power this train had a remote helper locomotive at the rear. Results from these revenue service tests provide additional credibility to the previously established validation of TEDS that was based on data from published and publicly available sources [2].

1.2 Objectives

TEDS software consists of subsystem models of the coupling and automatic air brake systems that are the foundation for the overall system level model. It is the goal of this effort to conduct validation of the overall system level model.

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 revenue service train tests for system level validation

The first two elements were used during TEDS development and initial validation [2–4]. This report, along with the report on the revenue service unit train test completed in 2016 [1], addresses the third element: system level validation based on data collected from an instrumented revenue service train.

When the validation approach was defined for the TEDS model [2], the following three criteria were established:

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'[1] (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

[1] AAR Manual of Standards and Recommended Practices Brakes and Brake Equipment-Standard S-486

(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.[2] 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.

The acceptance criteria used for TEDS validation in this report are summarized in Table 1-1. These criteria are the same as used in previous efforts for TEDS validation.

Table 1-1. Acceptance criteria for validating TEDS

Parameter	Criterion	Acceptance
Coupler Forces	Occurrence	Predict synchronization in timing and location
	Trend	Show correct trend
	Magnitude	Predict peaks (>100,000 lbs.) within ±20%
Airbrake	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 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, including an emergency application, performed with the train stationary. Stopping tests were conducted, with associated slack action and distance traveled compared to simulated results. Dynamic braking tests were not included since that method of operation is not utilized on the test route.

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

[2] Draft is a term used for railroad couplers in tension, and buff is a term used for railroad couplers in compression.

1.5 Organization of Report

This report details the development of the test plan in Section 2; Section 3 provides information on how the tests were executed; Section 4 describes the TEDS simulations and compares it to the test data; and Section 5 summarizes the work completed and overall results.

2 Test Plan Development

2.1 Pre-Test Tasks

SA with the Indiana Northeastern Railroad (INRR), arranged for a short line railroad operating in northeastern Indiana, northwestern Ohio and southeastern Michigan, to host the revenue service validation tests on INRR's property. Among other commodities, the INRR moves agricultural and industrial products, including fertilizers and chemicals, serving local grain elevators and businesses, and interchanges with a Class I railroad in Montpelier, OH.

2.1.1 Route/Track Selection

The route selected for these validation tests corresponds to the INRR movement of a mixed manifest train from the Class I railroad interchange point to various local customers, at about 43 miles altogether.

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

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

Test data was collected from mile 5 to the top of the hill at mile 48 in Figure 2-1.

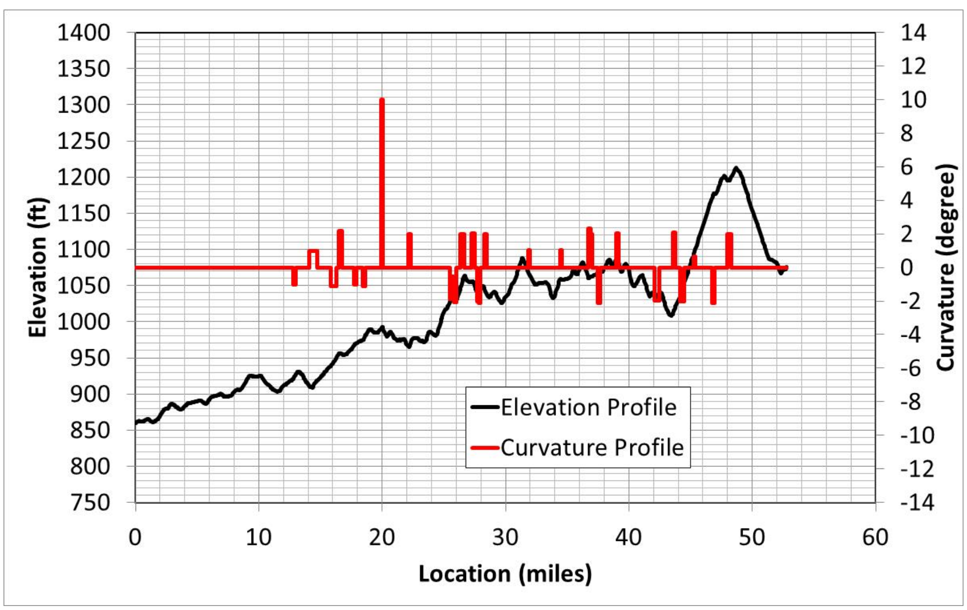

Figure 2-1. Track Elevation and Curvature profile

2.2 Instrumentation

Several planning meetings were held between SA and INRR at the railroad's shop. SA presented test plans and discussed the schedule and logistics of pre-test instrumentation and procedures with INRR for train operation on the days of the tests.

Locomotives and test cars were inspected to confirm their suitability for the planned instrumentation. The instrumentation for this test was similar to that used in the first revenue service test [1].

Figure 2-2. SoMat eDAQlite

A SoMat eDAQlite 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 at each end of the train were obtained using the SoMat Global Positioning System (GPS) module, as shown in Figure 2-3.

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, car body acceleration, and brake system pressure on the three instrumented test cars.

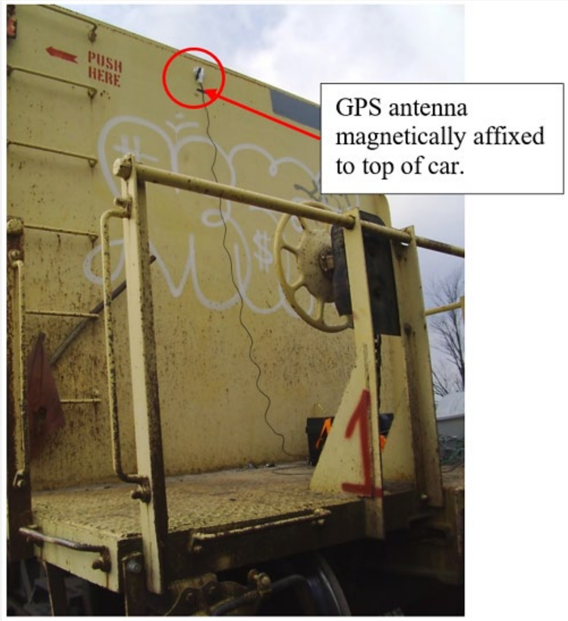

Figure 2-3. GPS antenna installed on Test Car #1

Throttle position at both locomotive consists (i.e., lead and remote) was collected by recording the states of the engine governor control trainline signals. A 27-pin multiple unit (MU) cable was modified to capture and direct these signals to the SoMat data collection, as shown in Figure 2-4. The modified MU cable is shown connected to the rear of the trailing unit in the lead consist, adjacent to the data collection system on Test Car #1. The engine governor control trainline signals were 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.

Figure 2-4. Modified MU cable (yellow) for collecting throttle position

One of the most important parameters 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. TE is a function of the train speed and the throttle position (i.e., idle, 1 to 8). 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 (e.g., motor #2) was measured and this value was assumed to be representative of all motors on that locomotive. This procedure is consistent with the method used by the locomotive manufacturers to display traction motor amps or TE on the engineer's control panel and stored in the event recorder. From this data, the locomotive characteristic curves—TE versus speed and throttle notch—were constructed and used by TEDS to estimate the TE as delivered at the rail.

The GP-40 (i.e., the lead locomotive in the leading consist) control system uses transducers for traction motor current and voltage feedback. SA tapped into the signals from the relevant conductors at the corresponding computer connectors (Figure 2-5).

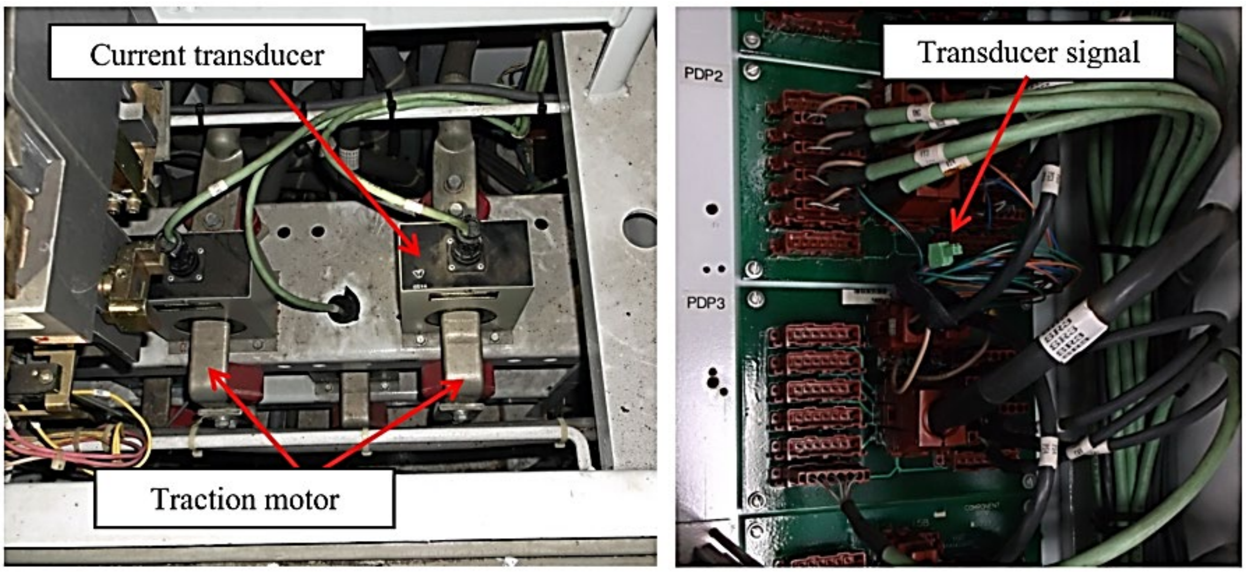

Figure 2-5. Traction motor current transducer and computer patch panel on lead locomotive

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 (i.e., the trailing unit in the lead consist and the lead unit in the remote consist) 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 the transition contactor terminals in the electrical cabinet. A voltage divider circuit was used to reduce the signal to the instrumentation input level (Figure 2-6). Motor current was obtained using a separate direct current transducer installed around one of the motor leads (Figure 2-7).

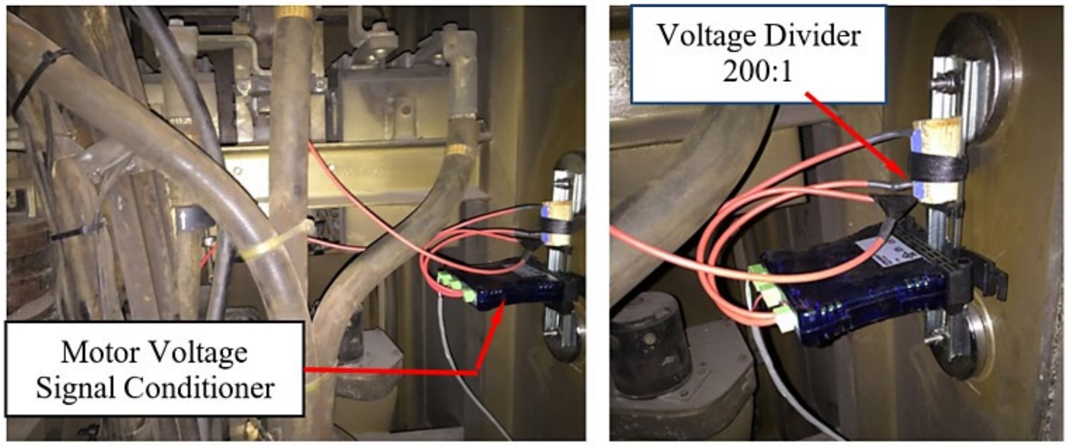

Figure 2-6. Traction motor voltage measurement on GP-30 locomotives

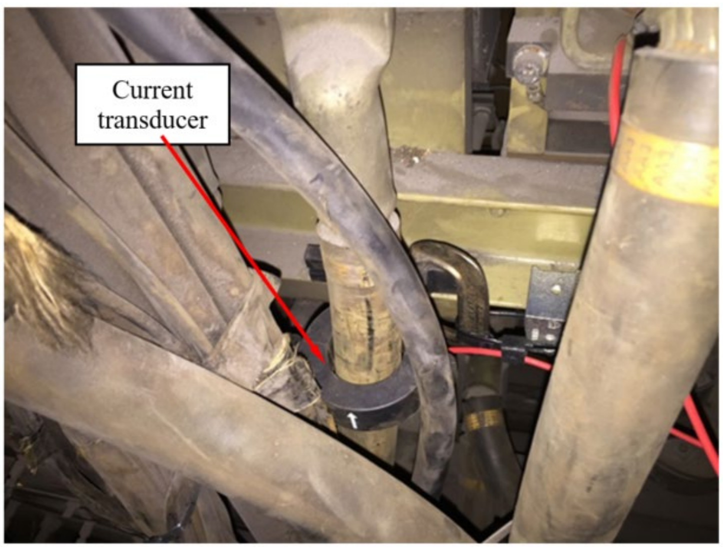

Figure 2-7. Current transducer installed around traction motor lead, GP-30 locomotives

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

Lead locomotive air brake pressures—equalizing reservoir 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).

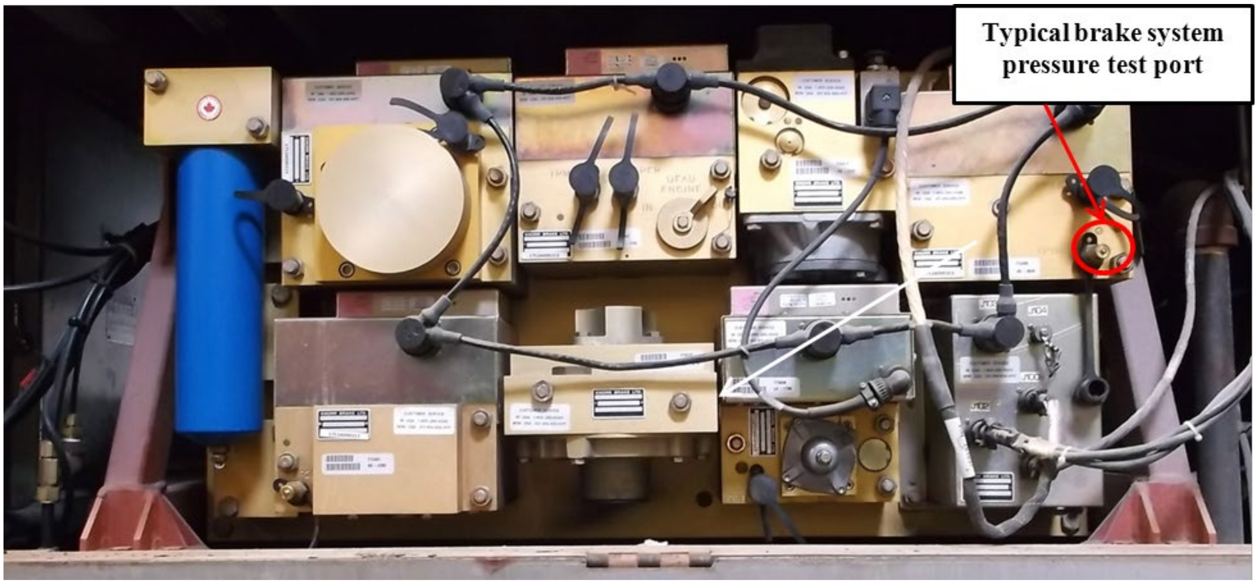

Figure 2-8. Electronic air brake equipment on the lead locomotive

In the remote locomotive (i.e., GP-30), the instrumentation for air brake pressures was connected to pneumatic taps inside the control stand. Air brake tubing was modified to provide tees into the equalizing reservoir and brake cylinder lines for these taps. Equalizing reservoir instrumentation is shown in Figure 2-9; brake cylinder pressure was obtained in a similar fashion.

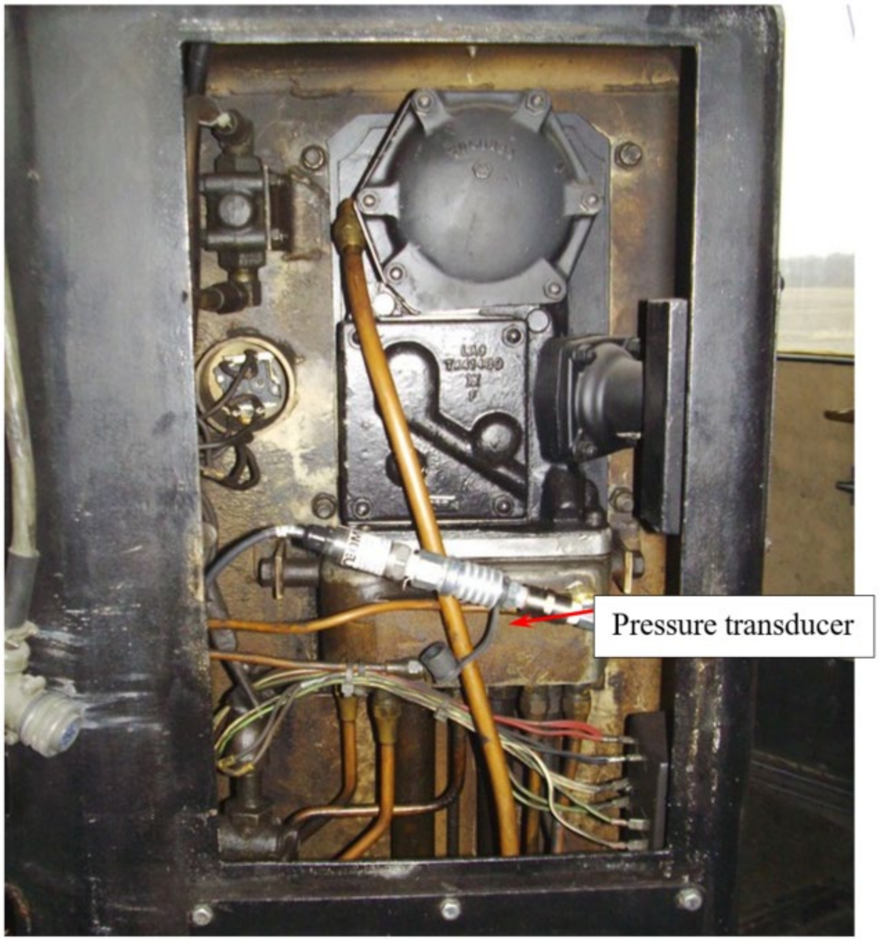

Figure 2-9. Pressure transducer attached to equalizing reservoir tap in remote locomotive

All three instrumented test cars had truck-mounted brake systems with the control valve and reservoirs located at the B-end under the slope sheet. Control valves on the test cars, which had been acting erratically during the first test, were replaced with recently rebuilt and tested DB-60 control valves, with a test expiration date of August 2017.

Brake system pressures were measured with the transducers connected, via quick-disconnect couplings, to test ports that had been installed for the unit train test. Brake cylinder, brake pipe, auxiliary reservoir and emergency reservoir pressures were monitored at each test car. Air brake instrumentation, including pressure transducers, quick-disconnect fittings, and the new control valve, on Test Car #1 are shown in Figure 2-10. The other two test cars had similar air brake instrumentation.

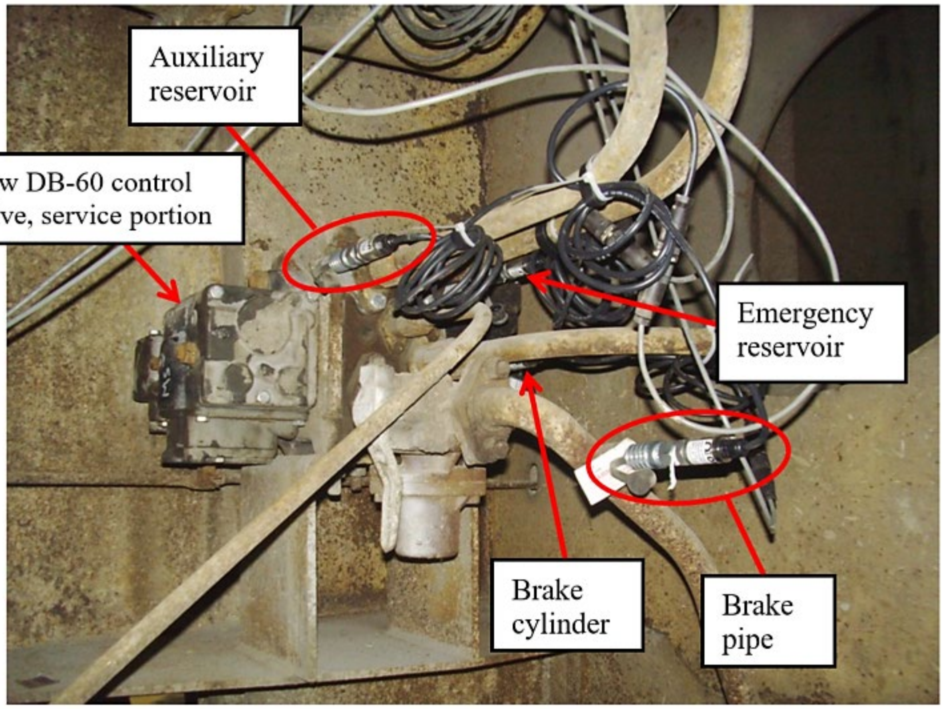

Figure 2-10. New control valve and air brake instrumentation on Test Car #1

Accelerometers were mounted on each test car, on the deck just above the center sill, to measure the carbody longitudinal acceleration due to slack action (Figure 2-11).

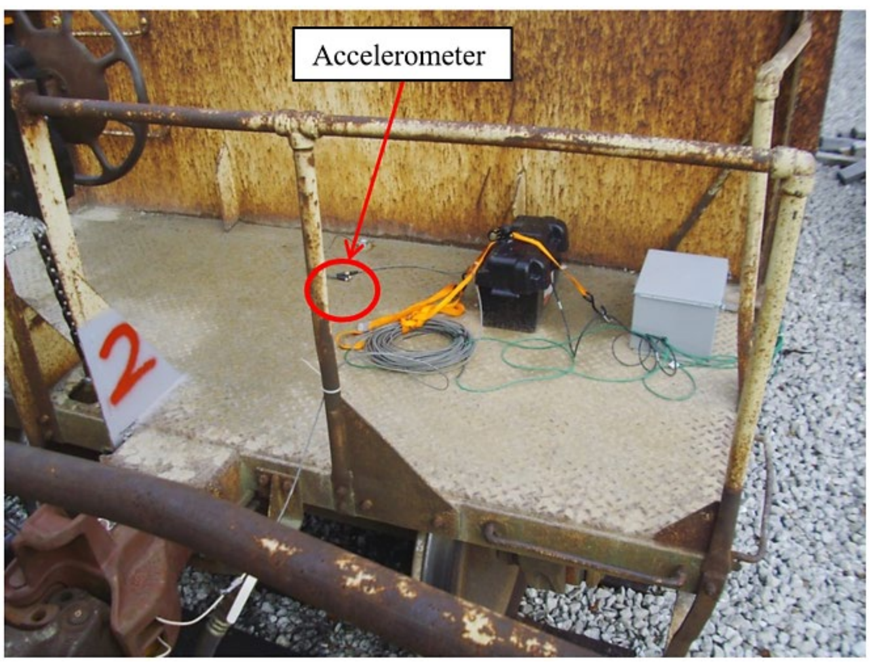

Figure 2-11. Accelerometer installed on a typical test car

Coupler forces were measured with dynamometer couplers. Special order, solid-shank couplers were fitted with strain gages and calibrated in a million-pound load frame (Figure 2-12).

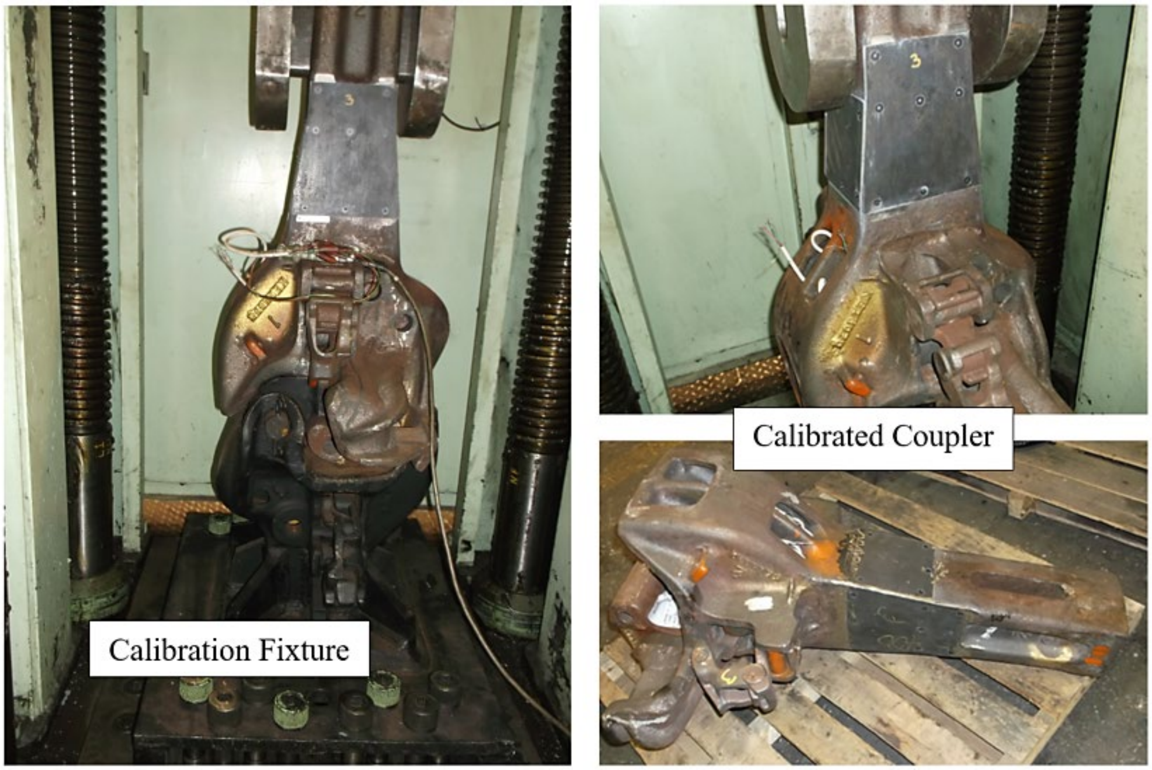

Figure 2-12. Dynamometer coupler calibration

Figure 2-13 shows the dynamometer coupler installed in Test Car #1 and coupled to the trailing locomotive of the lead consist. Figure 2-14 shows the same test car with the data acquisition equipment installed.

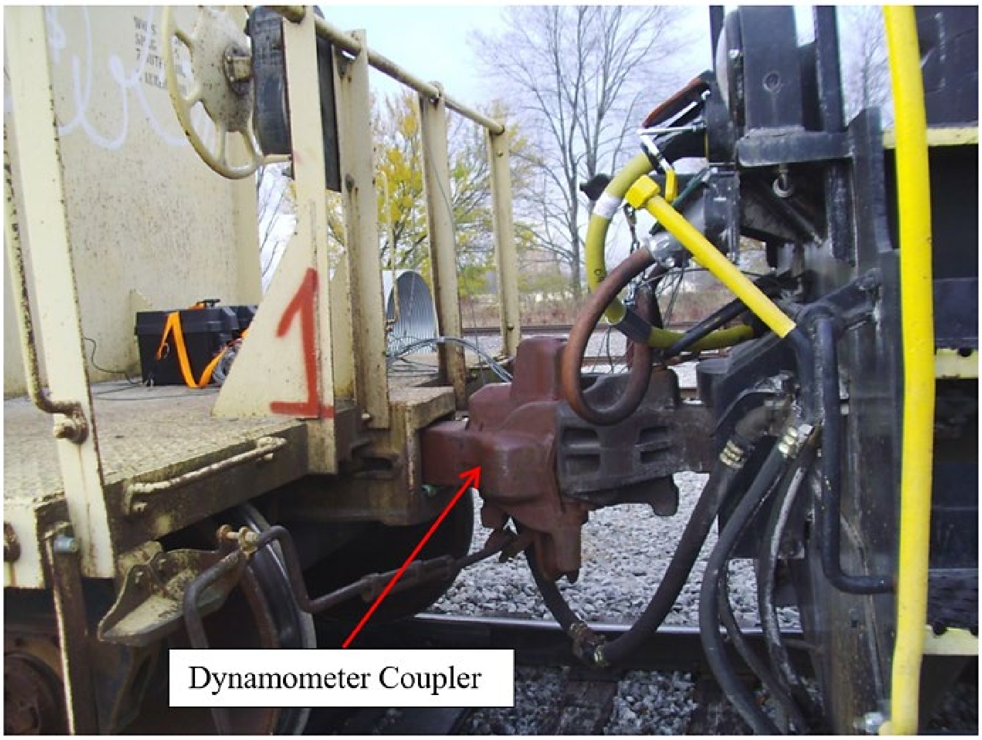

Figure 2-13. Dynamometer coupler installed on Test Car #1

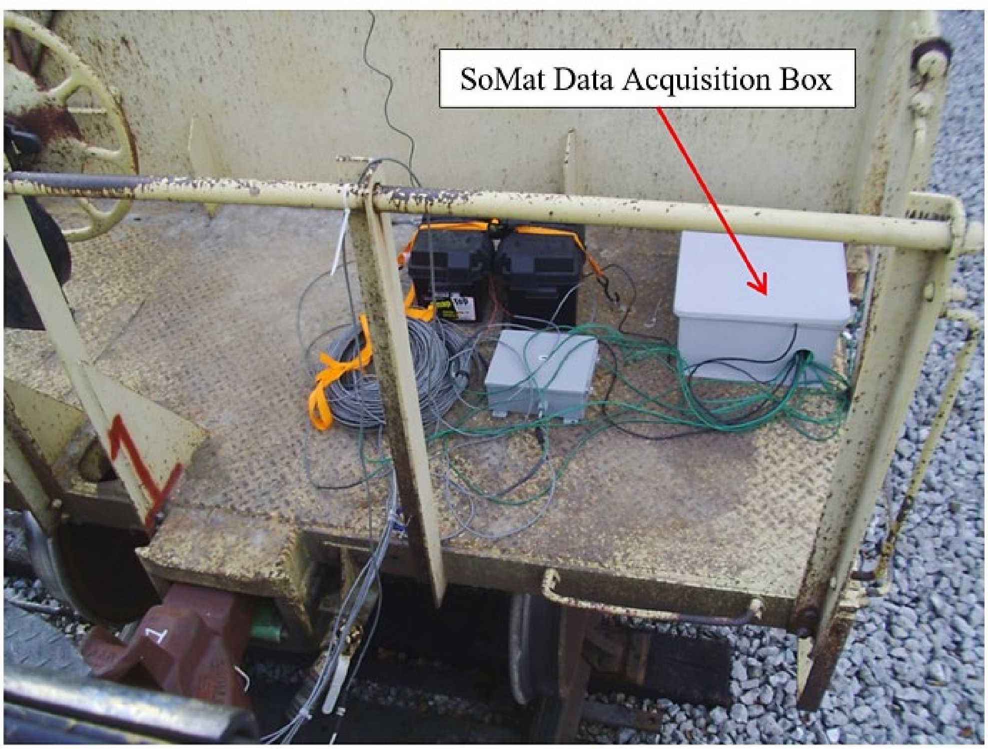

Figure 2-14. Data acquisition equipment mounted on Test Car #1

3 Revenue Service Test Execution

The planned tests were completed over 2 days, in December 2016. The weather during the two test days was generally clear and cold, with temperatures in the 15–20 °F range. The test train (Figure 3-1) was loaded and assembled on the first test day.

Figure 3-1. Locomotives and test cars after instrumentation

3.1 Test Train Configuration

The test train consist included 3 locomotives, 3 test cars, and 54 mixed interchange freight cars. The test consist was a mixed train of loaded and empty cars. The test cars were loaded with gravel. The first two locomotives provided traction at the head of the consist, and the remote locomotive provided traction at the end of the consist. Through radio communication between the engineer at the lead locomotive and the engineer at the remote locomotive, throttle position and braking maneuvers were synchronized in a manual, distributed power scheme. Air brake MU hoses were connected, so all locomotives participated in braking.

The train configurations for day 1 and day 2 of the test were different, as 17 cars between the second locomotive and the first test car were delivered to a customer at the end of day 1.

The train consists for the two test days are shown in Table 3-1.

Table 3-1. Daily train consists

Train consist: Day 1	Train consist: Day 2
GP40-2: 3,000 hp (DOTX-2000) **GP30**: 2,250 hp	**GP40-2**: 3,000 hp (DOTX-2000) **GP30**: 2,250 hp
Test Car #1, Loaded instrumented end leading **33** Mixed cars (various empty and loaded) **Test Car #2**, Loaded instrumented end trailing **21** Mixed (various empty and loaded) **Test Car #3**, Loaded instrumented end trailing	**Test Car #1**, Loaded instrumented end leading **16** Mixed cars (various empty and loaded) **Test Car #2**, Loaded instrumented end trailing **21** Mixed (various empty and loaded) **Test Car #3**, Loaded instrumented end trailing
GP30: 2,250 hp **SD-40**: Dead in tow for transfer to yard	**GP30**: 2,250 hp

The overall train characteristics for the 2 days of testing are summarized in Table 3-2.

Table 3-2. Overall train characteristics

	Day 1 Testing	Day 2 Testing
Locomotive power	7,500	7,500
Trailing tons	4,596	2,962
Train length, feet	3,495	2,571
Number of cars	57	40

The standing air brake applications tests were conducted on the train at the assembly site. The train then departed at about 5:00 pm after completion of the initial terminal brake test. The test train was operated over approximately the first 27 miles of the planned route and then was stopped for the night at 6:45 pm.

At this point, in addition to the first 17 cars, the deactivated SD-40 at the end of the train was cut out of the train before testing on the second day. The revenue service tests resumed the following day.

Car loadings were obtained from Wheel Impact Load Detector (WILD) data provided to INRR by the railroad which handed the train to INRR.

Car reporting marks were obtained from video footage of the test train. Weights of the test cars, as loaded with gravel, were provided by INRR.

[Figure 3-2](#) and [Figure 3-3](#) illustrate the distributions of vehicle weight and length, respectively, in the simulated train for the first day of testing.

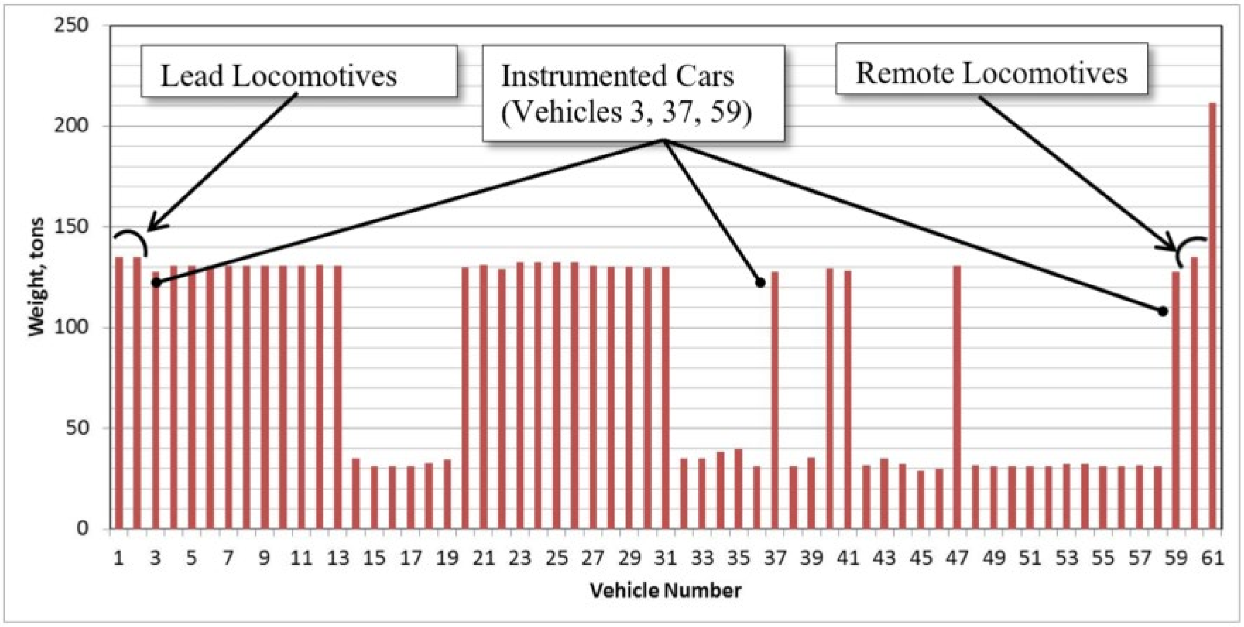

Figure 3-2. Vehicle weight distribution, simulated test train, day 1

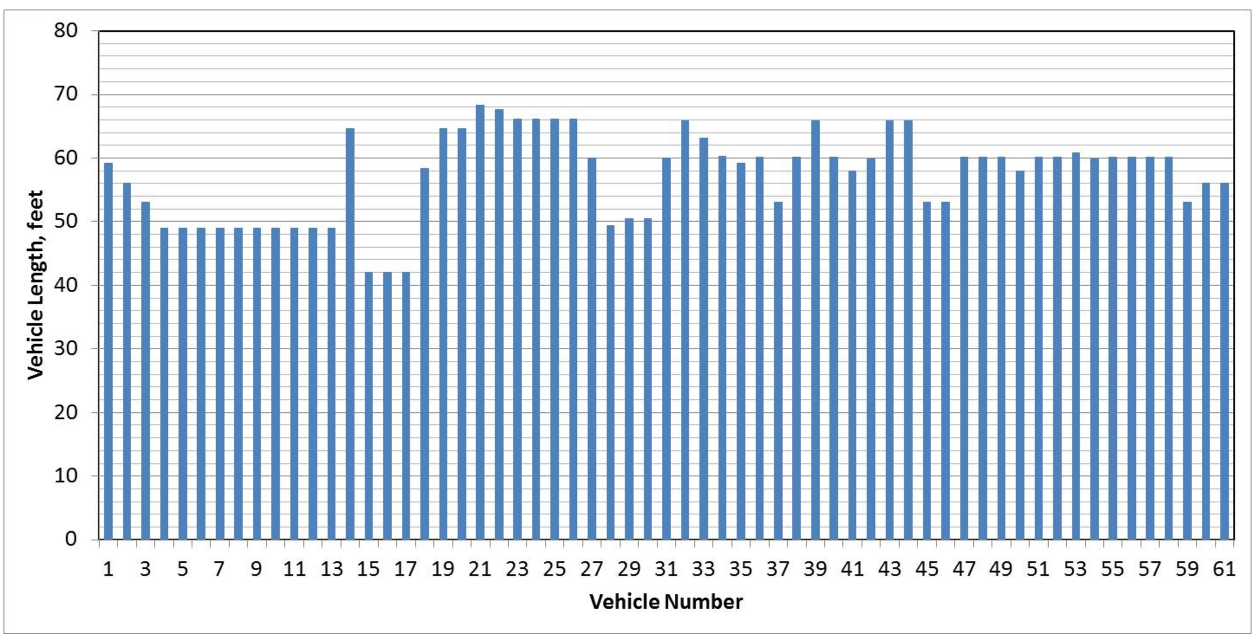

Figure 3-3. Vehicle length distribution, simulated test train, day 1

The vehicle weight and length distributions after setting out the first 17 cars as well as the SD-40 locomotive in the trailing locomotive consist for the second day of testing are shown in Figure 3-4 and Figure 3-5, respectively.

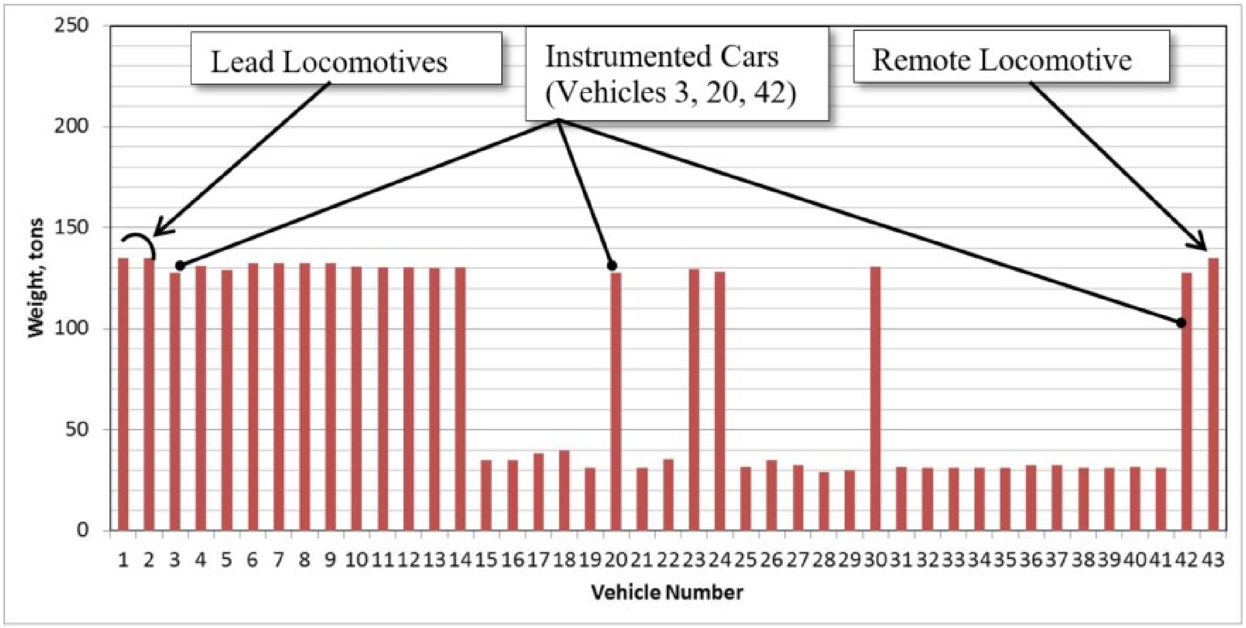

Figure 3-4. Vehicle weight distribution, simulated test train, day 2

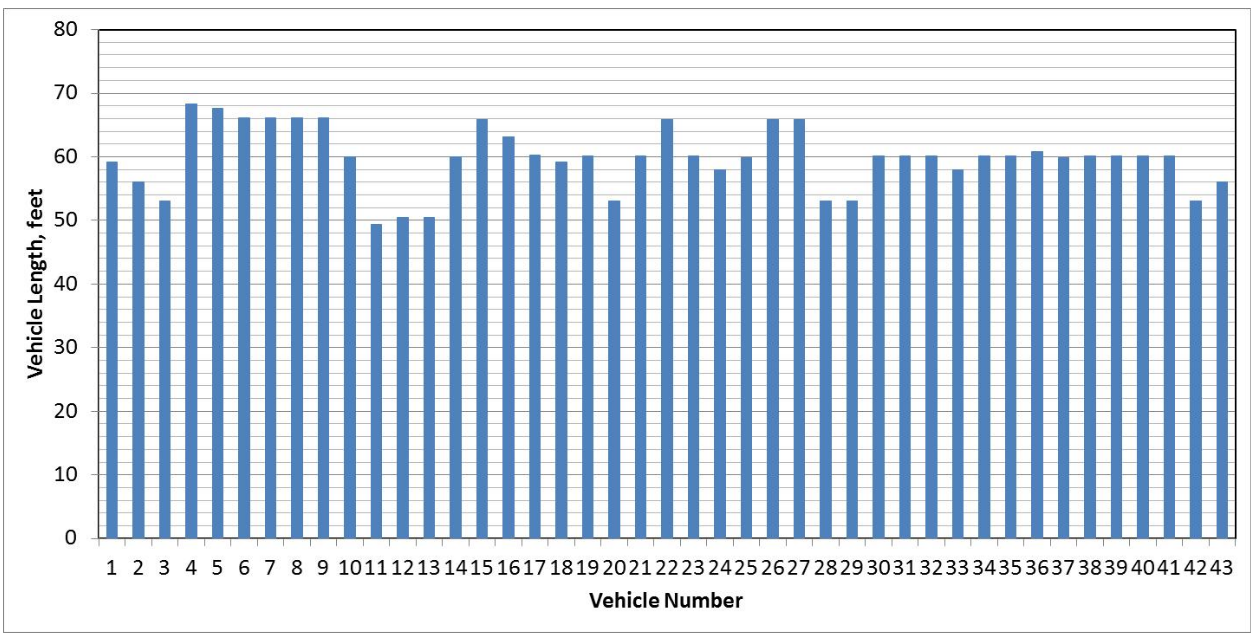

Figure 3-5. Vehicle length distribution, simulated test train, day 2

The brake pipe regulating pressure was 90 psi and the air flow rate to compensate for system leakage was minimal. A small assumed air flow value of 0.1 cfm was used in the TEDS simulations. This value was justified by the good match found later with the brake pipe pressures. None of the locomotives was equipped with dynamic braking. The lead locomotive was equipped with an electronic brake system, while the remaining locomotives had conventional 26-L type pneumatic brake systems. Braking ratios of the cars ranged from 8.5 to 12.5 percent. A braking ratio of 28 percent for the locomotives was assumed in the TEDS simulations.

3.2 Data Collection

Three INRR gravel cars, serving as instrumentation test cars, were distributed within the train consist. Each of the test cars was equipped with a standalone 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 lead locomotives was collected by the SoMat system on Test Car #1, located directly behind the trailing locomotive in the consist. Data from the remote locomotive was collected by the SoMat system on Test Car #3.

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

Figure 3-7 shows the location of the instrumentation on the locomotives and test cars.

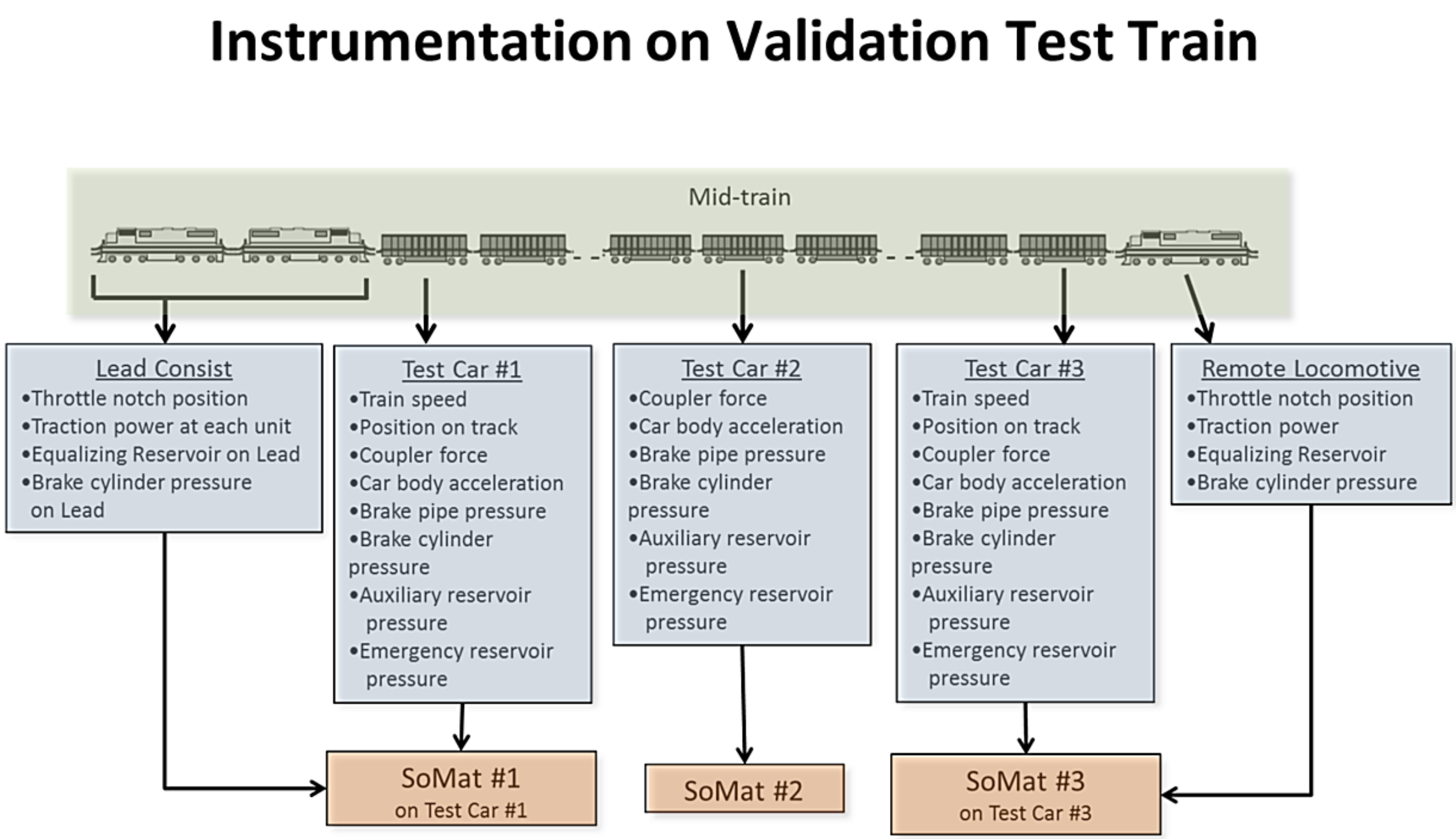

Figure 3-7. Instrumentation installed on the train

Details of the physical measurements collected are listed in Table 3-3. The speed and position (i.e., latitude and longitude) measurements were sampled every second. All other data was collected at 200 samples per second, with a filter of 67 Hz applied to the analog signal coming into the SoMat.

Table 3-3. Test train instrumentation

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

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

An SA employee rode in the test train lead locomotive cab and another SA employee rode in the test train remote locomotive cab to take notes during the test, to create landmark identification records in the test data, assist the engineer with interpreting the special test procedures, and collect other information to help create 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 and 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 connected into 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 over the range of operating conditions in this test.

3.3 Special Test

On the first day of testing, immediately after assembly of the test train and the installation of instrumentation system, a special series of tests was conducted before beginning the revenue service test.

While the train was still parked, a series of air brake applications and releases was performed for validation of the TEDS' air brake model. These tests were conducted with both the lead and remote locomotives controlling the brakes (i.e., the brake system was cut in on both ends of the train).

A full-service brake application was conducted first. After the system stabilized, the brakes were released, and an engineer-initiated emergency application was applied. The brakes were then released after the emergency application stabilized throughout the train. Since an emergency brake application is not a desired situation, the railroad agreed to let SA collect data for this scenario with the test train stationary, thus not violating any operating rules.

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. Special air brake testing conducted prior to train movement on the first day of testing
2. Train startup and stop from the initiating terminal
3. Train stop at the end of the first day of testing
4. Train stop at the end of the second day of testing, from a higher speed than event No. 3 above

It should be noted that the charts plotting the TEDS simulation results against distance use the location of the lead locomotive. Time-based data was synchronized among the three SoMat data collection systems, as described in Section 3.2.

All track locations are given in miles, measured from an arbitrary zero location well behind the train's starting point.

4.1 Initial Full Service and Emergency Application

The special air brake testing described in Section 3.3 was conducted with the train stopped. Figure 4-1 shows the comparison of TEDS predicted brake pipe pressure and the measured brake pipe pressure on Test Car #1 for the air brake testing. TEDS matches the measured data very well. A similar match for Test Car #2 and Test Car #3 is shown in Figure 4-2 and Figure 4-3, respectively. The TEDS predictions of the brake cylinder pressure for the three test cars match the measured test data very well as shown in Figure 4-4, Figure 4-5, and Figure 4-6.

The steady-state cylinder pressure on Test Car #2 at about 50 psig service and 74 psig emergency was less than on Test Car #1 and Test Car #3, which were about 64 psig service and 78 psig emergency. SA suspects this is due to a larger brake cylinder volume on Test Car #2. A larger cylinder volume requires a greater amount of air mass to fill to obtain the same pressure compared to a smaller volume. Since the control valve on a car laps (closes) when the auxiliary reservoir pressure falls to the level of the brake pipe pressure, a specific mass of air is directed to the cylinder for a given brake pipe reduction. Therefore, a cylinder with a larger volume will have a lower pressure than a cylinder with a smaller volume. The cylinder stroke on Test Car #2 was increased from 8 inches to 11 inches to model this effect. Since the predicted brake cylinder pressure on Test Car #2 matched the measured trend well, this value was used in all subsequent simulations.

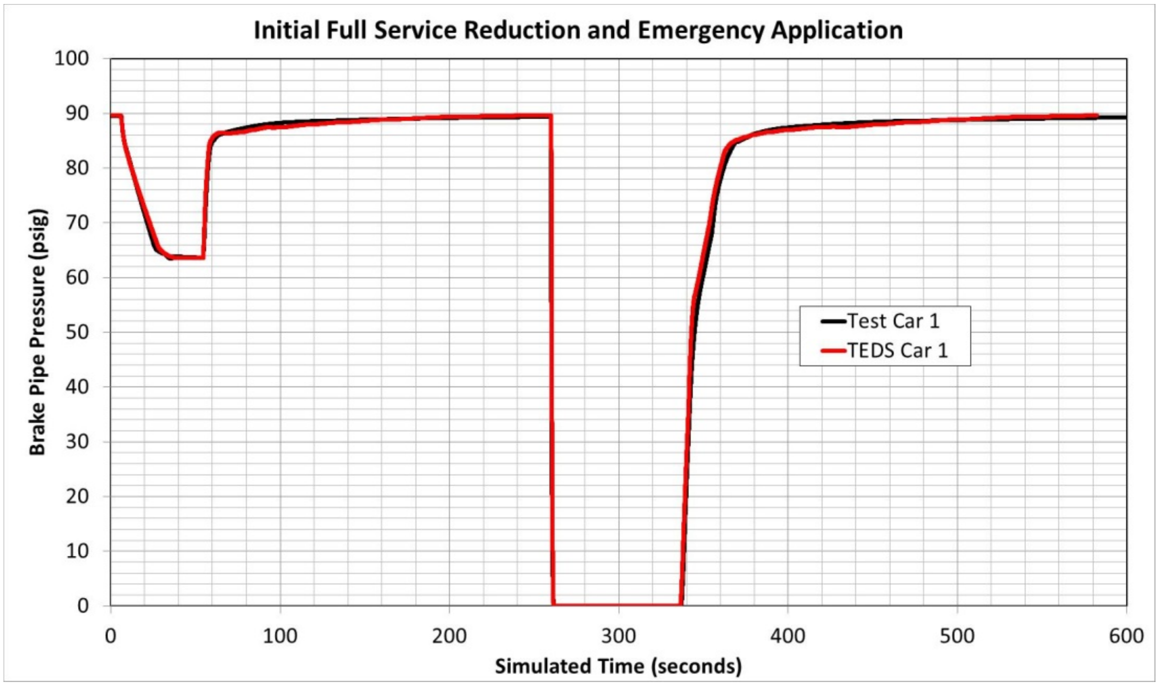

Figure 4-1. Comparison of measured test data and TEDS predicted brake pipe pressure on Test Car #1 for the air brake test

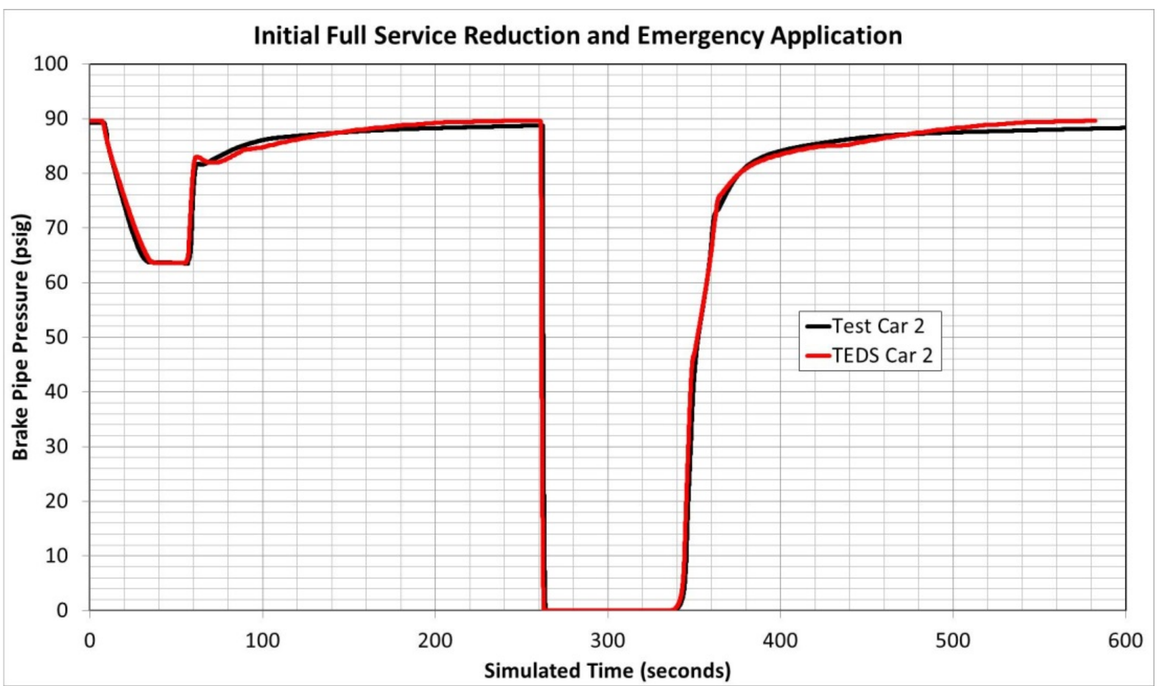

Figure 4-2. Comparison of measured test data and TEDS predicted brake pipe pressure on Test Car #2 for the air brake test

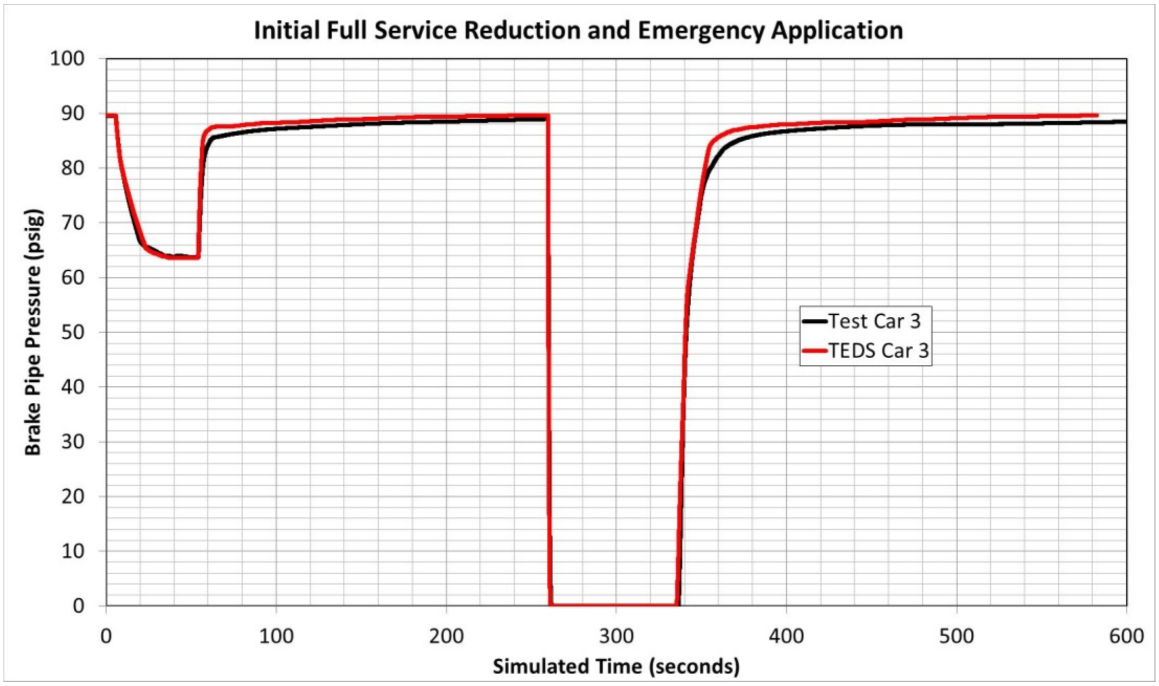

Figure 4-3. Comparison of measured test data and TEDS predicted brake pipe pressure on Test Car #3 for the air brake test

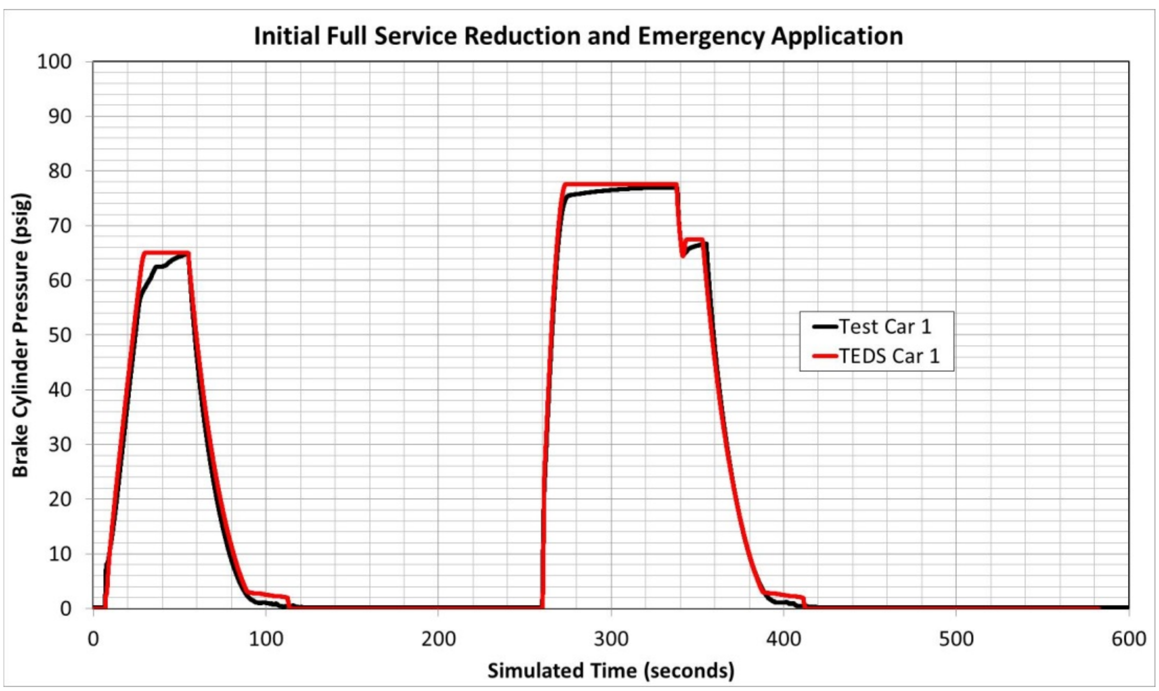

Figure 4-4. Comparison of measured test data and TEDS predicted brake cylinder pressure on Test Car #1 for the air brake test

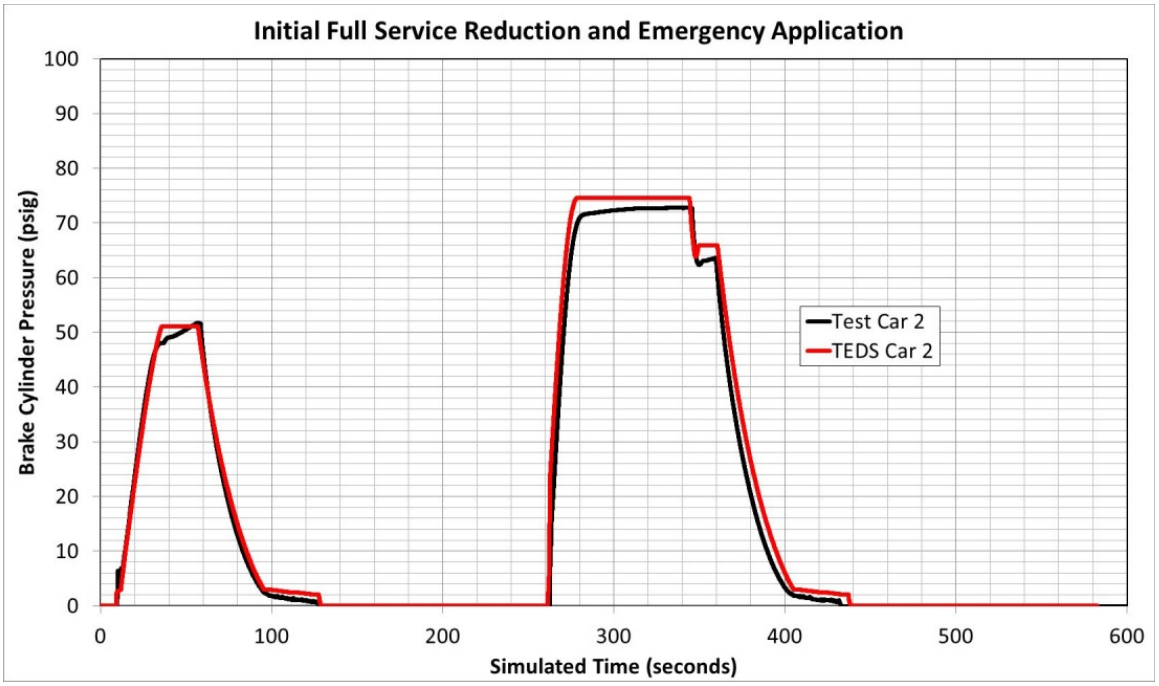

Figure 4-5. Comparison of measured test data and TEDS predicted brake cylinder pressure on Test Car #2 for the air brake test

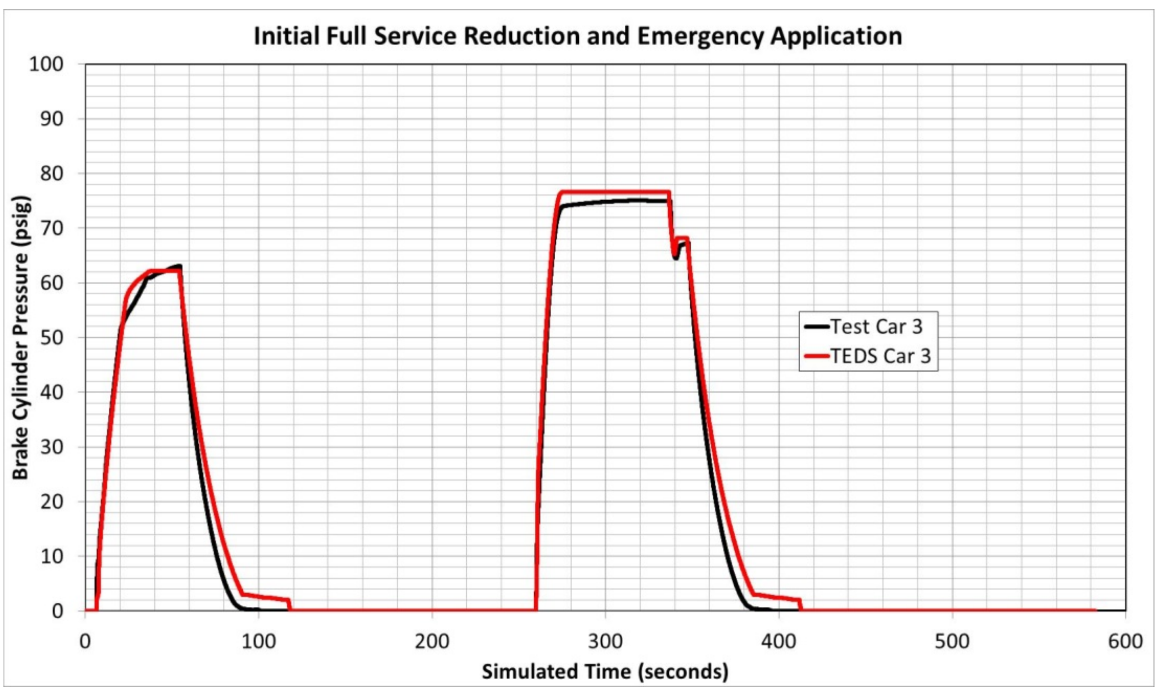

Figure 4-6. Comparison of measured test data and TEDS predicted brake cylinder pressure on Test Car #3 for the air brake test

To highlight the effect of a remote brake pipe controller—due to the rear end locomotive—an additional simulation was conducted to demonstrate the difference between having only a head-end controller and having head-end and remote controllers. It should be noted that head-end only applications were not performed in the actual standing brake test. During the running brake tests, only the head-end locomotive was controlling the brake pipe, i.e., applying and releasing the air brakes.

There are several noticeable differences in the brake pipe pressure behavior.

- First, as shown in Figure 4-7, there is a slight delay of about 6 seconds for the pneumatic signal to reach Test Car #3, which is near the rear end of the train, when the brake pipe is controlled from the head-end only.
- Second, the drop-in brake pipe pressure is more gradual at Test Car #3 with a brake pipe controller at the head-end only. This is consistent with not having an additional source of brake pipe venting (i.e., the remote locomotive) nearby.
- Third, the release takes longer and it is clear that with only the head-end brake pipe controller active, the auxiliary reservoir on Test Car #3 could not have become fully charged prior to the initiation of the emergency application. This explains why the brake cylinder pressure in the subsequent emergency application was not as high as when the remote locomotive was also cut in.
- Finally, the release from emergency takes much longer with only the head-end brake pipe controller. Similar to the release from service, it is clear that at the end of the simulation, for the case with only the lead brake pipe controller active, the auxiliary and emergency reservoirs could not have become completely charged.

The effect of not having a remote brake pipe controller on the brake cylinder is shown in Figure 4-8. The brake cylinder pressure builds much more slowly for the service application when there is no remote brake pipe controller, consistent with the slower brake pipe reduction. The service release is not significantly affected, except for a slight delay in initiation due to the delay in seeing the brake pipe rise.

The slopes of the emergency buildup and emergency release are the same in both cases (i.e., a function of the local control valve). However, due to the much slower increase in brake pipe pressure during the emergency release, the brake cylinder pressure begins to release nearly 100 seconds later.

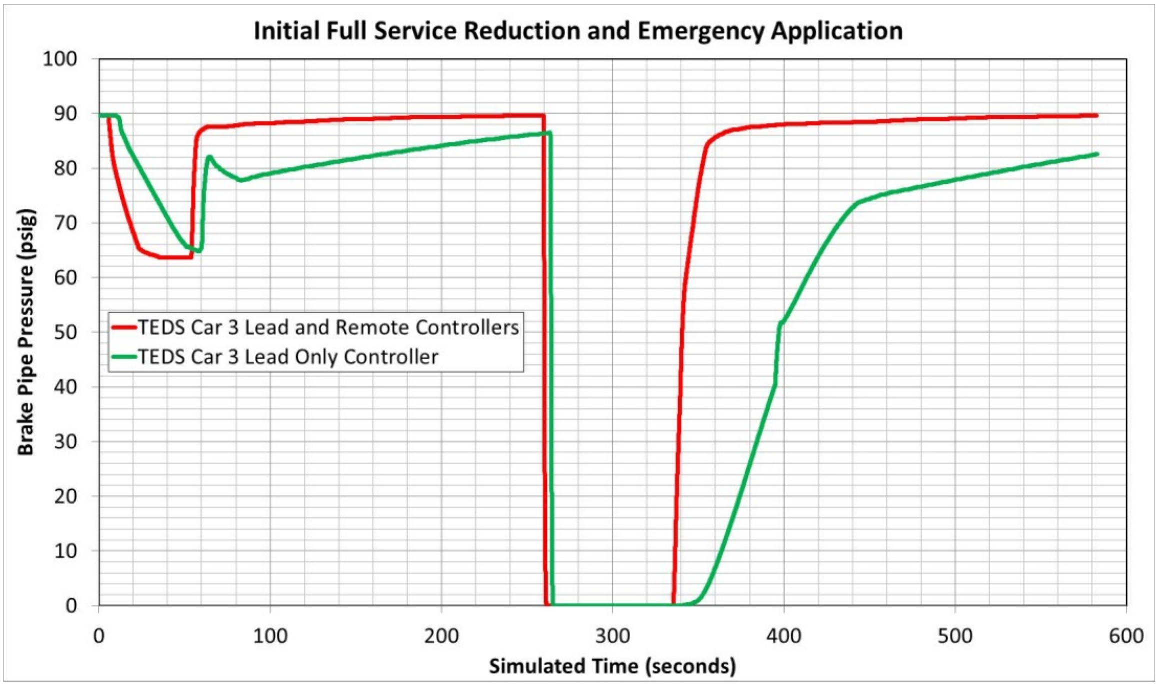

Figure 4-7. Comparison of Test Car #3 brake pipe pressure with and without the remote brake pipe controller

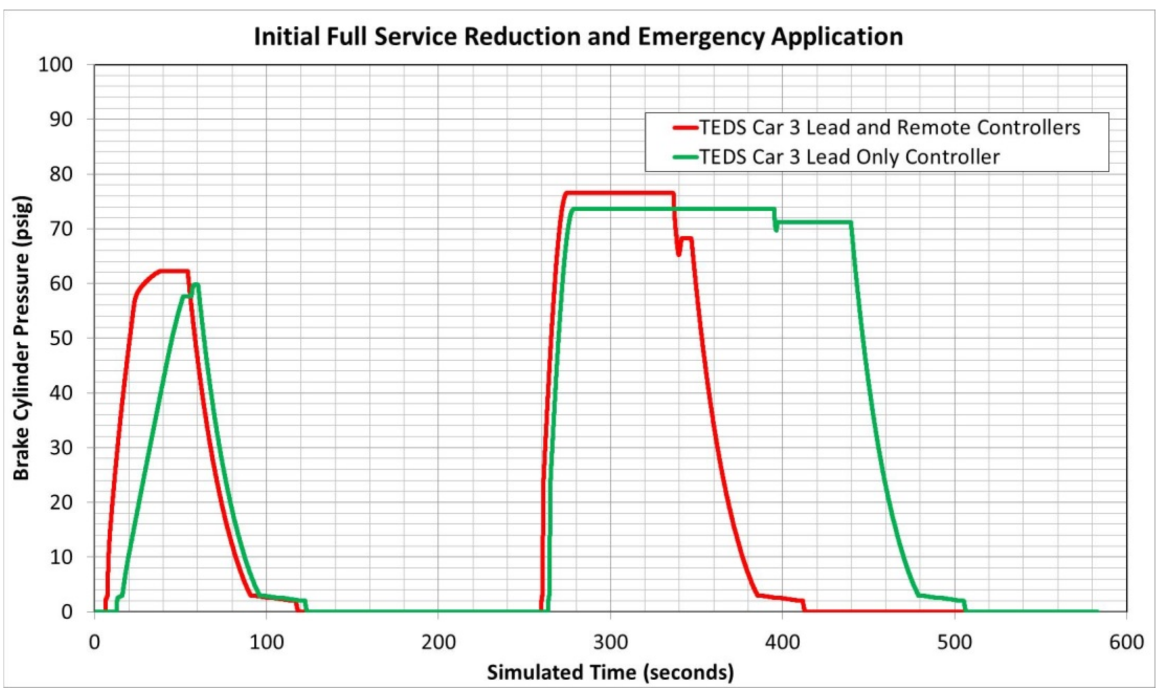

Figure 4-8. Comparison of Test Car #3 brake cylinder pressure with and without the remote brake pipe controller

4.2 Train Startup and Stop, Day 1 of Testing

The train negotiated undulating terrain just after its initial startup on the first day of testing as shown in Figure 4-9. The notch position and brake pipe pressure are shown in Figure 4-10. Figure 4-11 shows the measured speed and track profile. Air brake control was conducted at the head end of the train only, as the remote locomotive was not activated as a brake pipe controller.

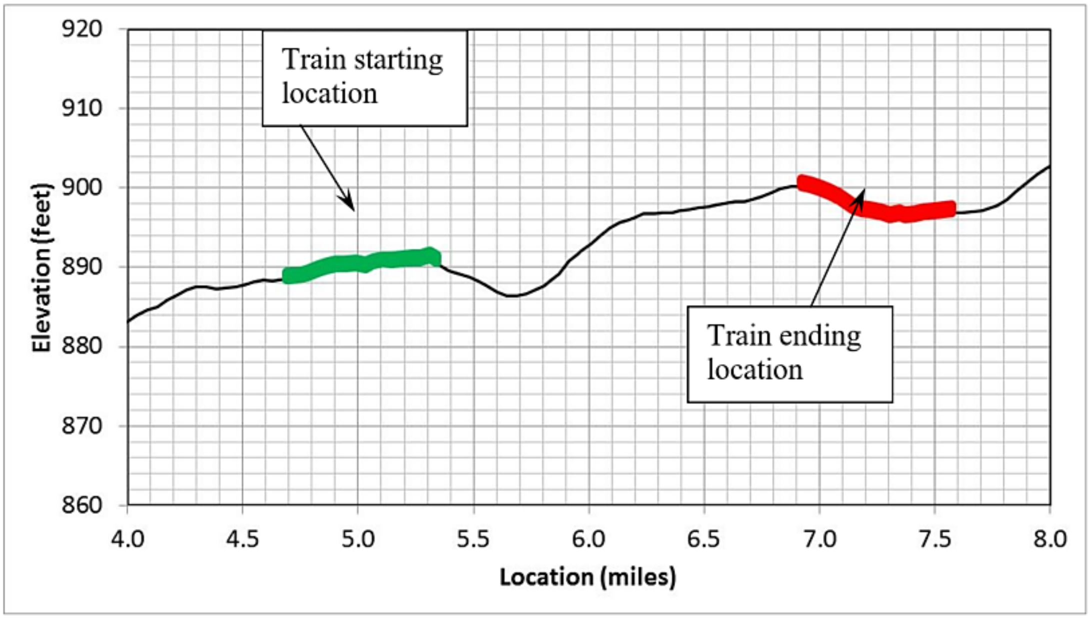

Figure 4-9. Track profile for day 1 initial startup and stop

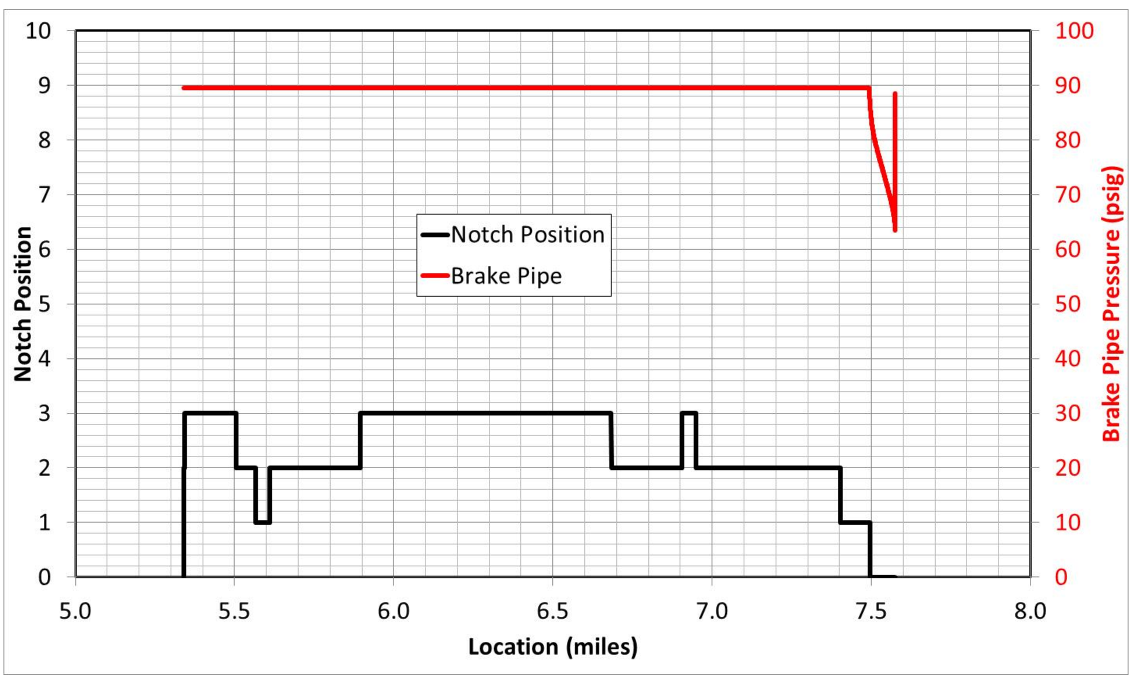

Figure 4-10. Notch position and brake pipe pressure for day 1 initial startup and stop

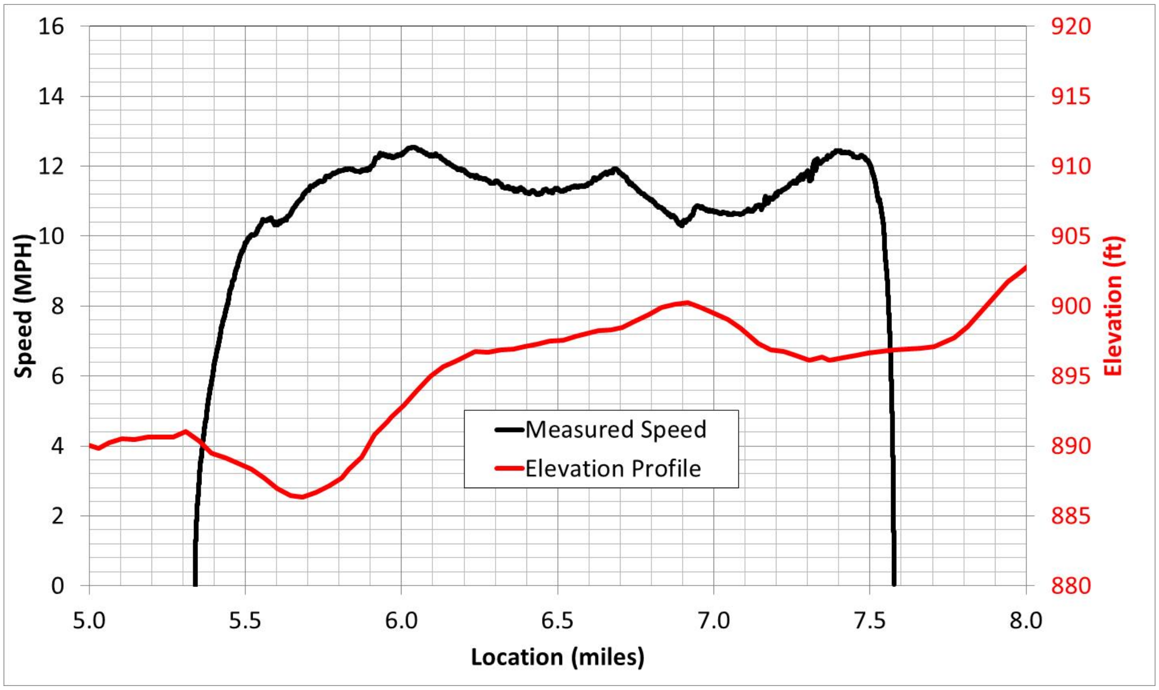

Figure 4-11. Measured speed and track profile for day 1 initial startup and stop

Train Speed

The measured train speed is compared to the speed predicted by TEDS in Figure 4-12. Although the overall operating train speed is low, the match between the TEDS prediction and the measured speed is excellent. The maximum discrepancy is less than 1 mph. The discrepancy should be viewed in the context of track grade and throttle changes over the 2 miles of train travel. During this travel, the grade changes were subtle but the throttle was changed four times.

The match between TEDS predicted speed and the measured speed is within the validation acceptance criterion of 2 mph difference described in Section 1.3.

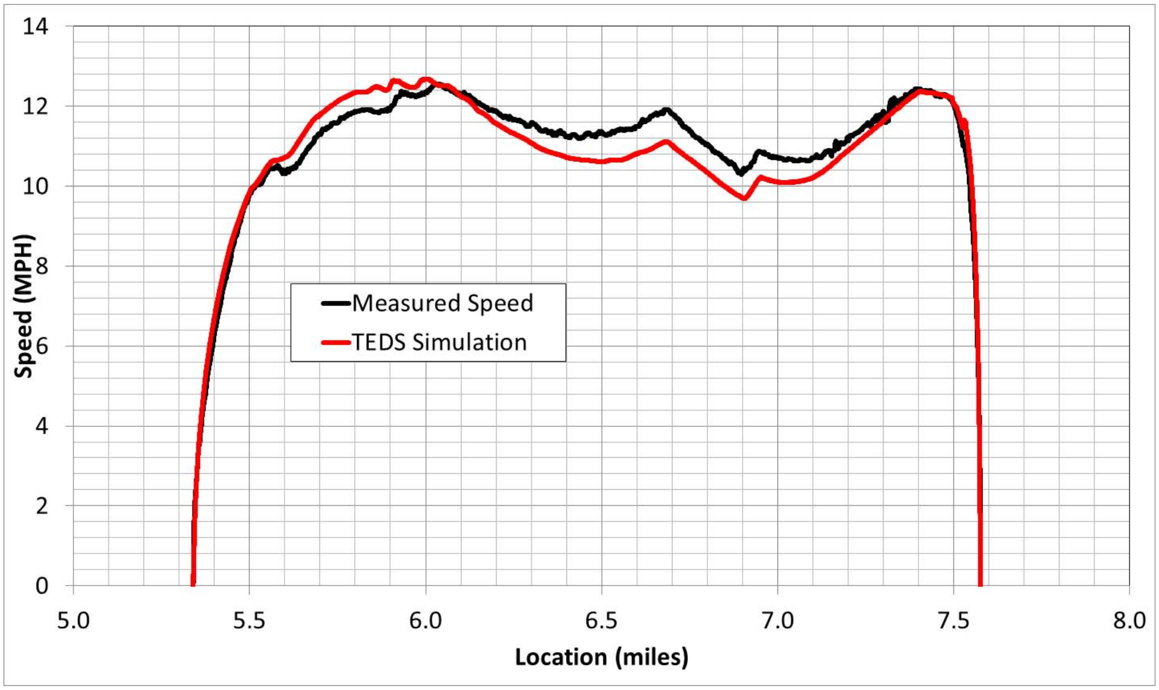

Figure 4-12. Measured and predicted speeds for day 1 initial startup and stop

Coupler Forces

The comparison between the measured and predicted coupler forces on Test Car #1 is shown in Figure 4-13. The predicted coupler force follows all the trends due to train handling and terrain changes very well. The train was on a relatively shallow grade and with low tonnage the coupler forces for the event were quite low. It should be noted that the dynamometer couplers used in the test were calibrated for a 1,000,000-lb. load. Therefore, the accuracy of measured loads at the lower end of the range is not as reliable as towards the high end, and differences in the measured and predicted loads are slightly more pronounced for low coupler forces.

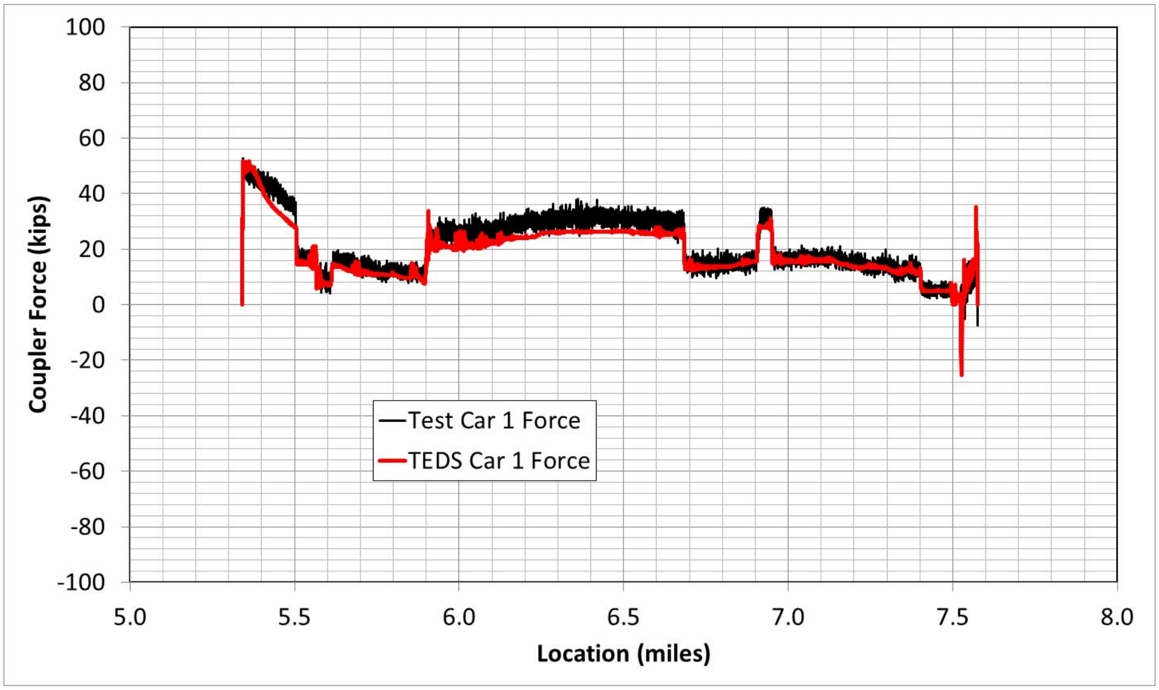

Figure 4-13. Measured and predicted coupler force on Test Car #1 for day 1 initial startup and stop

Figure 4-14 and Figure 4-15 compare the measured and predicted coupler forces on Test Car #2 and Test Car #3, respectively. Again, the predicted coupler force follows all the trends due to train handling and terrain changes very well, including the final large buff force on Test Car #3.

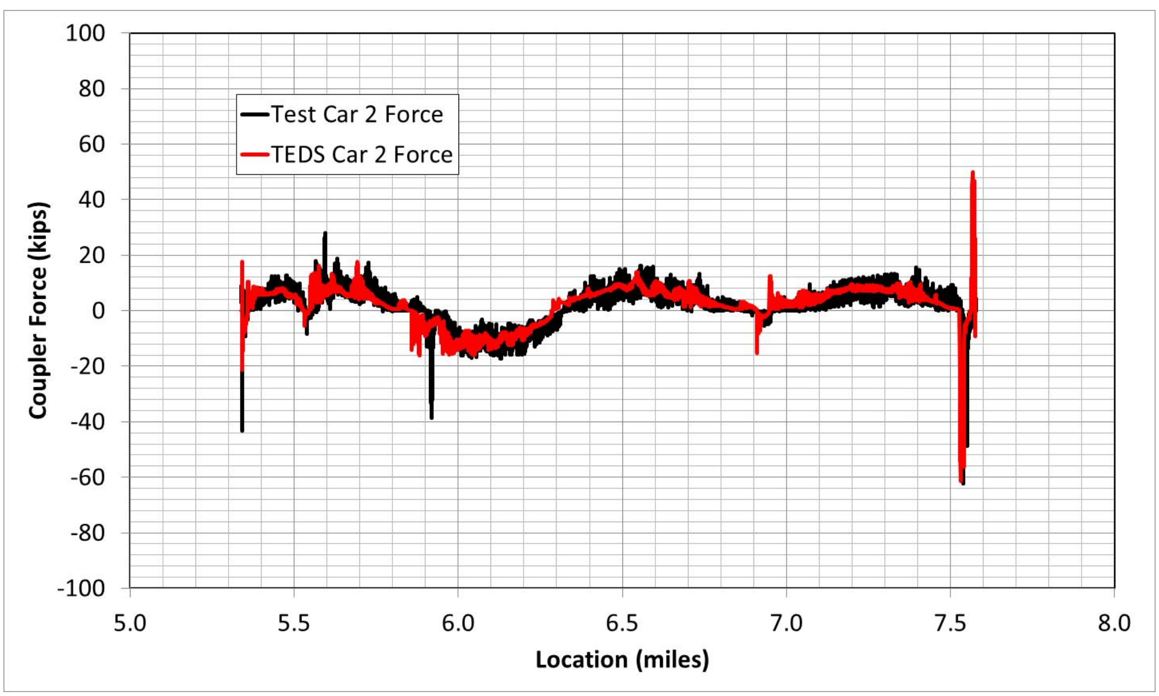

Figure 4-14. Measured and predicted coupler force on Test Car #2 for day 1 initial startup and stop

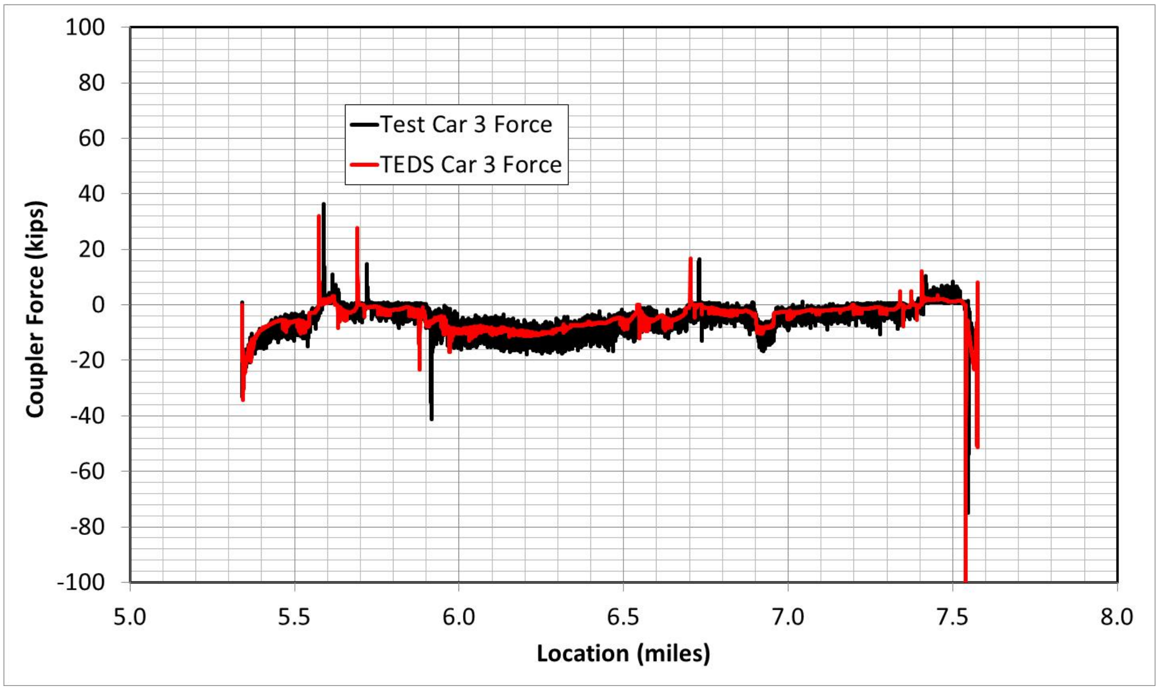

Figure 4-15. Measured and predicted coupler force on Test Car #3 for day 1 initial train startup and stop

Brake Pipe and Brake Cylinder Pressures

The measured and predicted brake pipe and brake cylinder pressures on Test Cars #1, # 2, and #3 are shown in Figure 4-16, Figure 4-17, and Figure 4-18, respectively. In all cases, the TEDS predictions closely match the measured values. The brake cylinder pressure on Test Car #2 is lower than both Test Car #1 and Test Car #3 due to a larger cylinder volume on Test Car #2 as described above.

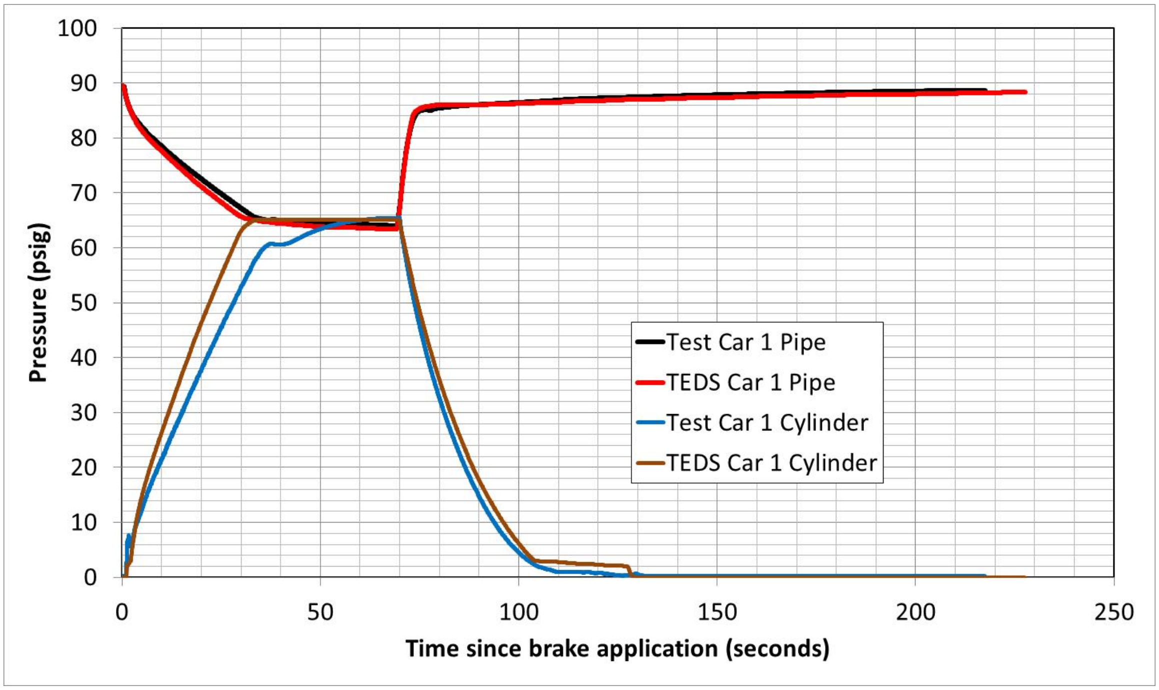

Figure 4-16. Measured and predicted brake pressures on Test Car #1 for the initial train startup and stop test

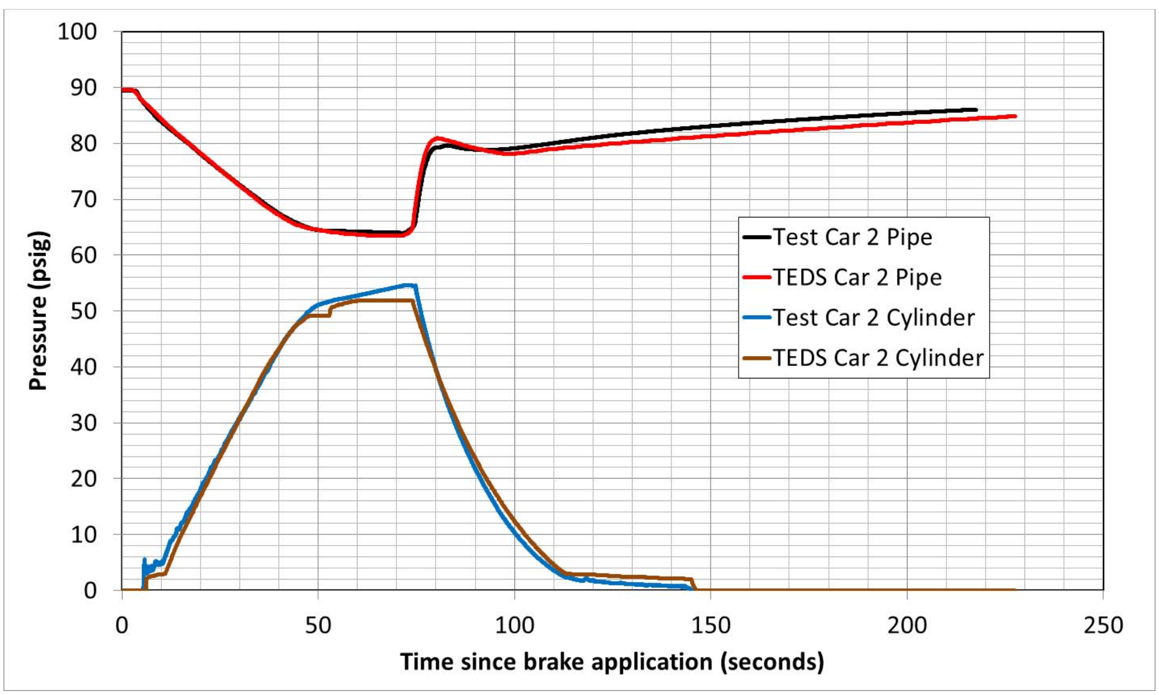

Figure 4-17. Measured and predicted brake pressures on Test Car #2 for day 1 initial startup and stop

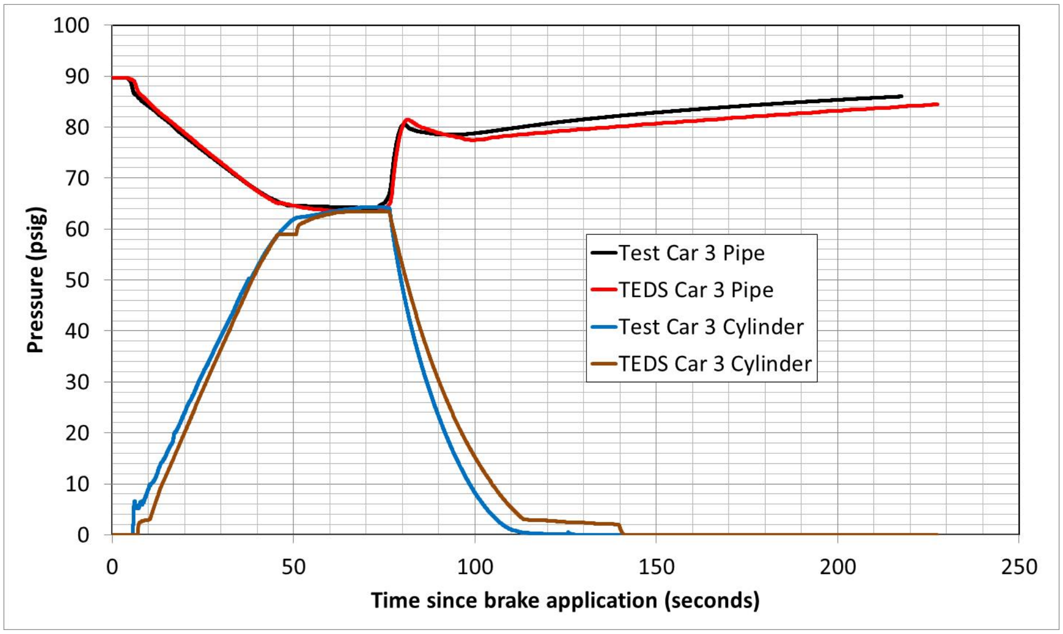

Figure 4-18. Measured and predicted brake pressures on Test Car #3 for day 1 initial startup and stop

4.3 End of Day 1 Air Brake Stop

The third event chosen to validate the TEDS simulation of the mixed train test was the stop at the end of day 1 of testing. Figure 4-19 shows the notch position, brake pipe cylinder pressure, and measured train speed for this stop. Air brake control was conducted from the head end of the train only, as the remote locomotive was not activated as a brake pipe controller.

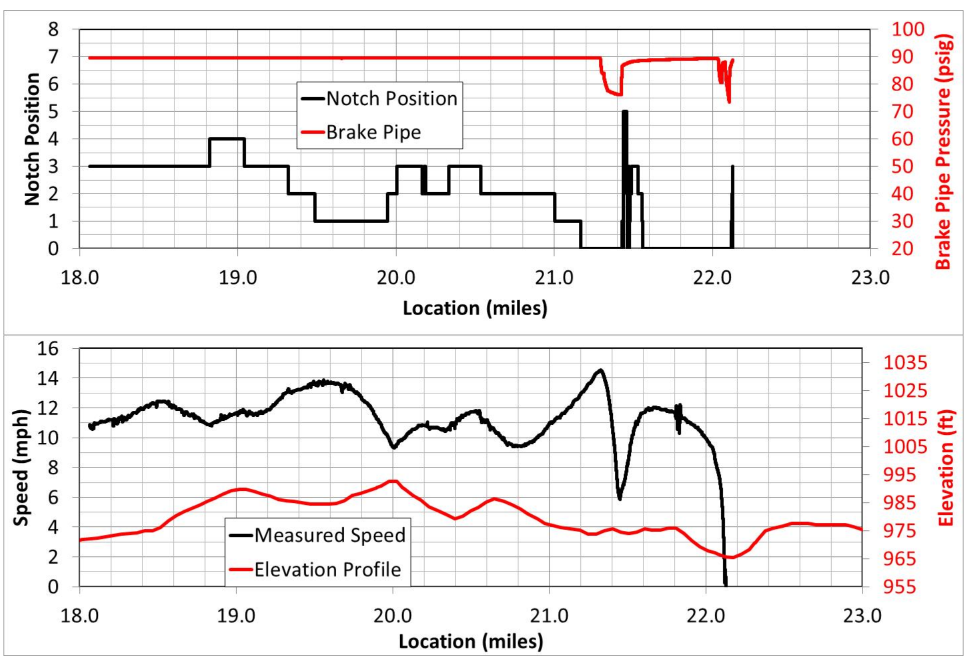

Figure 4-19. Notch, brake pipe pressure, elevation and train speed, end of day 1 stop

Figure 4-20 shows the train starting and ending locations on the track. The train traversed undulating territory during this 4-mile segment of track.

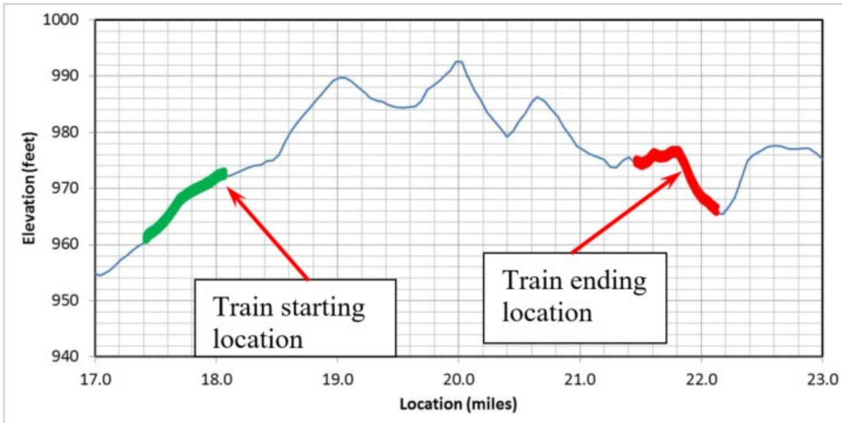

Figure 4-20. Train location on the track profile, end of day 1 stop

Train Speed

Figure 4-21 shows the comparison between the measured speed and the speed predicted by TEDS. The train handling and terrain changes are well represented. The rapid change in the measured speed near the end at about mile 21.8 does not appear in the TEDS prediction. These spikes in the speed are likely not realistic. For example, the first upward spike is nearly 1 mph and occurs over a period of 1.055 seconds, while the first downward spike is 1.56 mph and occurs about 2 seconds later, immediately following the first upward spike. It is not reasonable to expect that the large mass of the locomotive can gain and then lose that much kinetic energy over such a short period of time. Therefore, SA assumed this to be a spurious signal and ignored it in the comparison with TEDS.

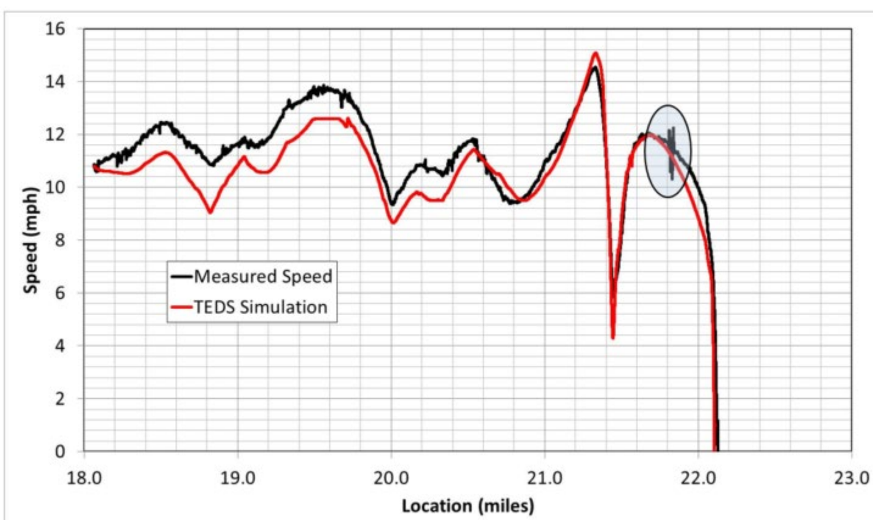

Figure 4-21. Measured and predicted train speeds, end of day 1 stop

Coupler Forces

The coupler force on Test Car #1 is shown in Figure 4-22. The match is well within the acceptance criterion. TEDS predicted all the spikes and came within 10 kips of highest peak. The same excellent match for the coupler forces on Test Car #2 and Test Car #3 is shown in Figure 4-23 and Figure 4-24, respectively.

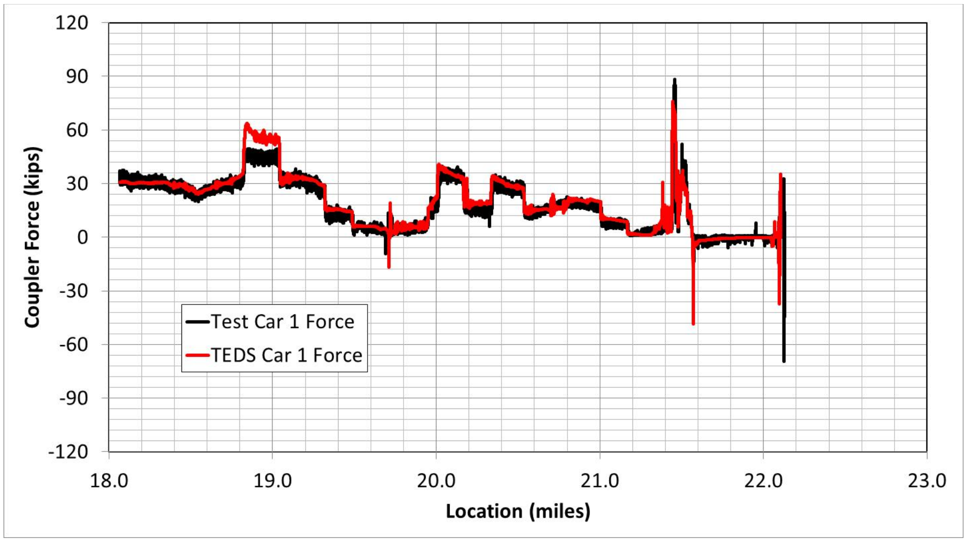

Figure 4-22. Measured and predicted coupler force on Test Car #1, end of day 1 stop

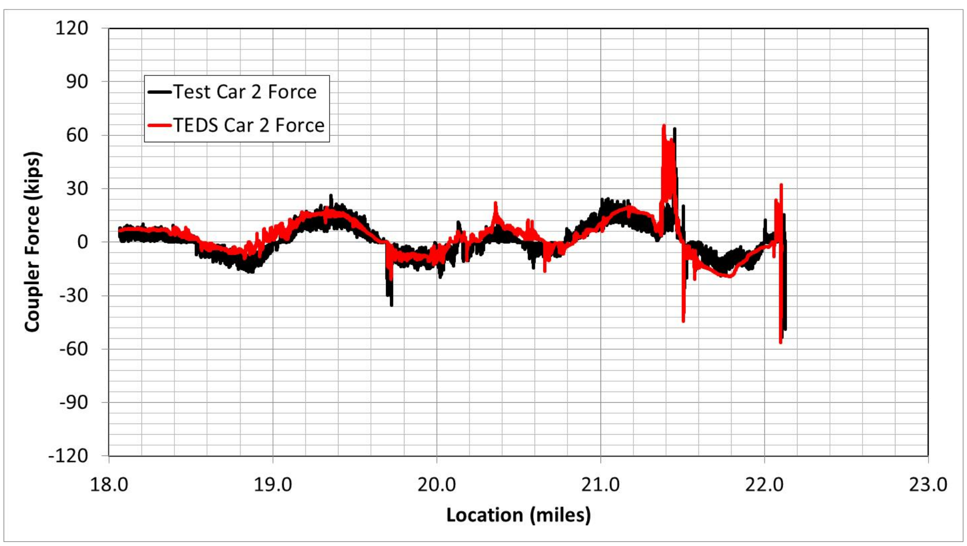

Figure 4-23. Measured and predicted coupler force on Test Car #2, end of day 1 stop

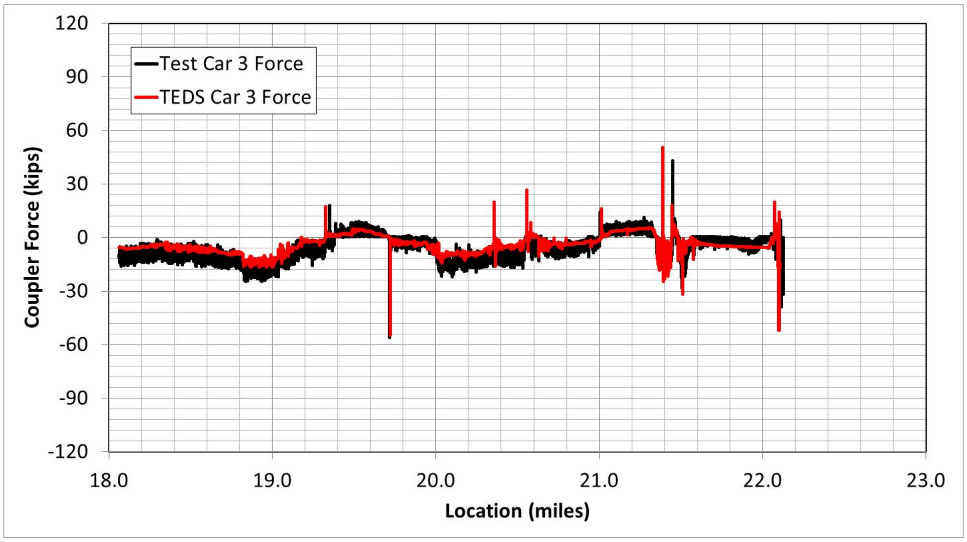

Figure 4-24. Measured and predicted coupler force on Test Car #3, end of day 1 stop

Brake Pipe and Brake Cylinder Pressures

The brake pipe and brake cylinder pressures on the three test cars are shown in Figure 4-25, Figure 4-26, and Figure 4-27. The use of the air brake to control train speed was required between miles 21.25 and 21.5, where a 13.5 psig reduction was applied. The brakes were released and then reapplied when approaching the stopping location.

The match between the TEDS predictions and the measured pressures is well within the acceptance criterion for both the brake pipe and brake cylinder on all three test cars. The effect of the larger cylinder volume on Test Car #2 compared to Test Car #1 and Test Car #3 is seen in Figure 4-26 where the pressure reaches about 24 psig on Test Car #2 compared to 30 psig for the other test cars.

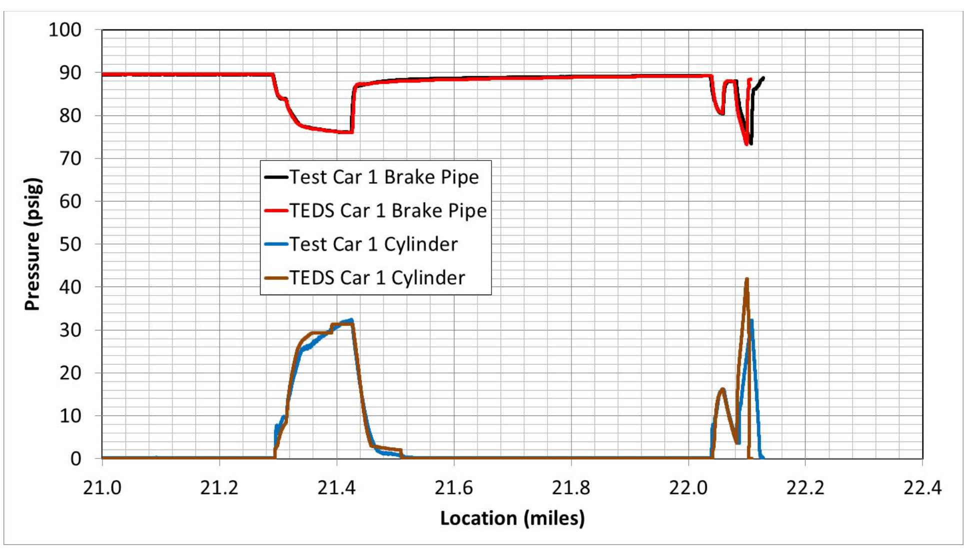

Figure 4-25. Measured and predicted pressures on Test Car #1, end of day 1 stop

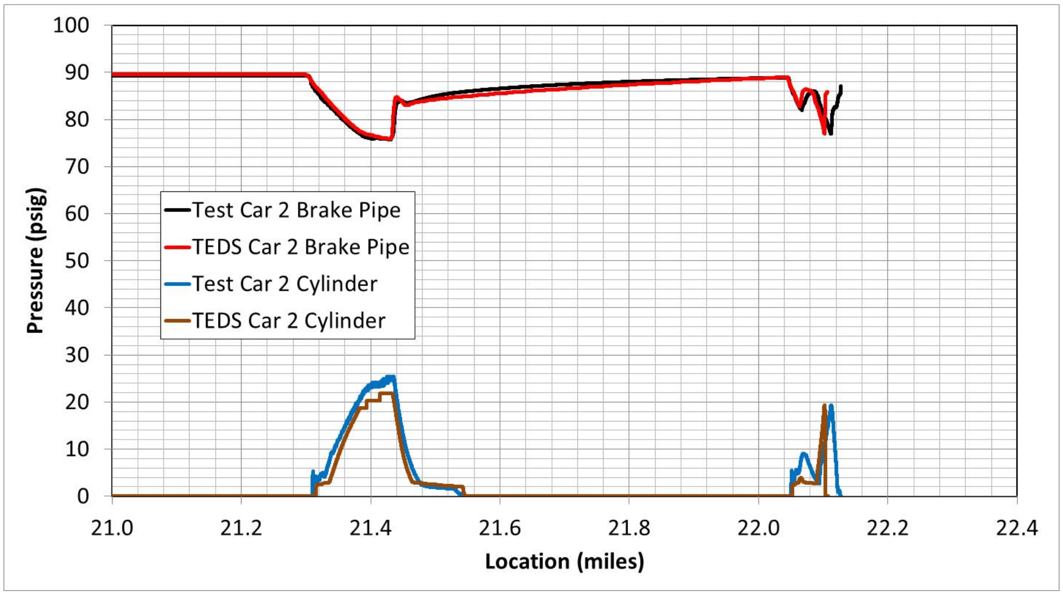

Figure 4-26. Measured and predicted pressures on Test Car #2, end of day 1 stop

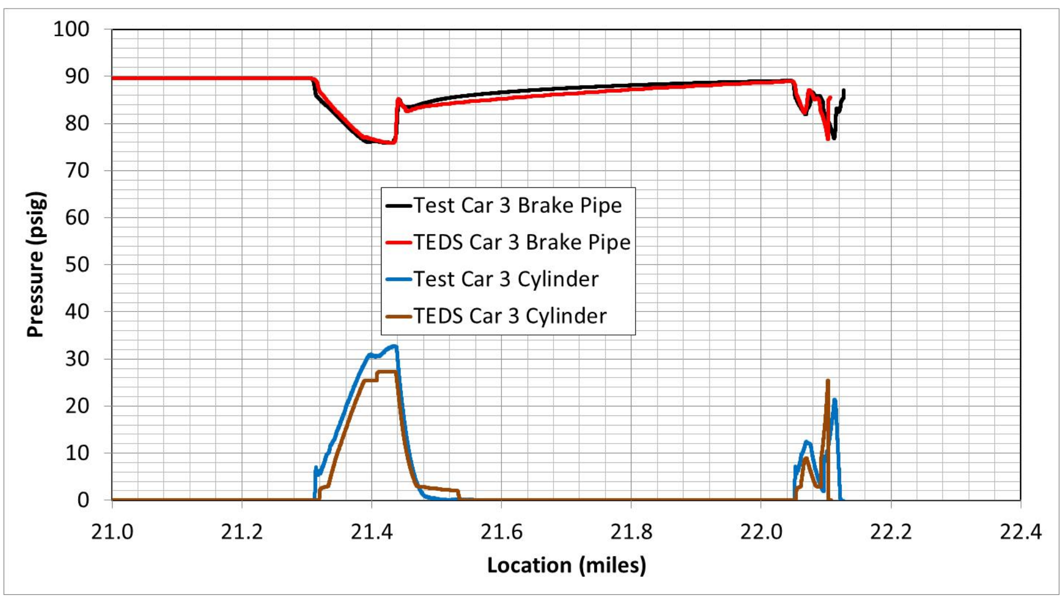

Figure 4-27. Measured and predicted pressures on Test Car #3, end of day 1 stop

4.4 End of Day 2 Air Brake Stop

The last event selected for simulation was the air brake stop completed at the end of the second day of testing. This stop was from a higher speed than the air brake stop at the end of the first day of testing.

The train handling, and speed and elevation profiles are shown in Figure 4-28. Air brake application control was conducted at the head end of the train only, as the remote locomotive was not cut in as a brake pipe controller. The beginning and ending positions of the train on the track profile are shown in Figure 4-29.

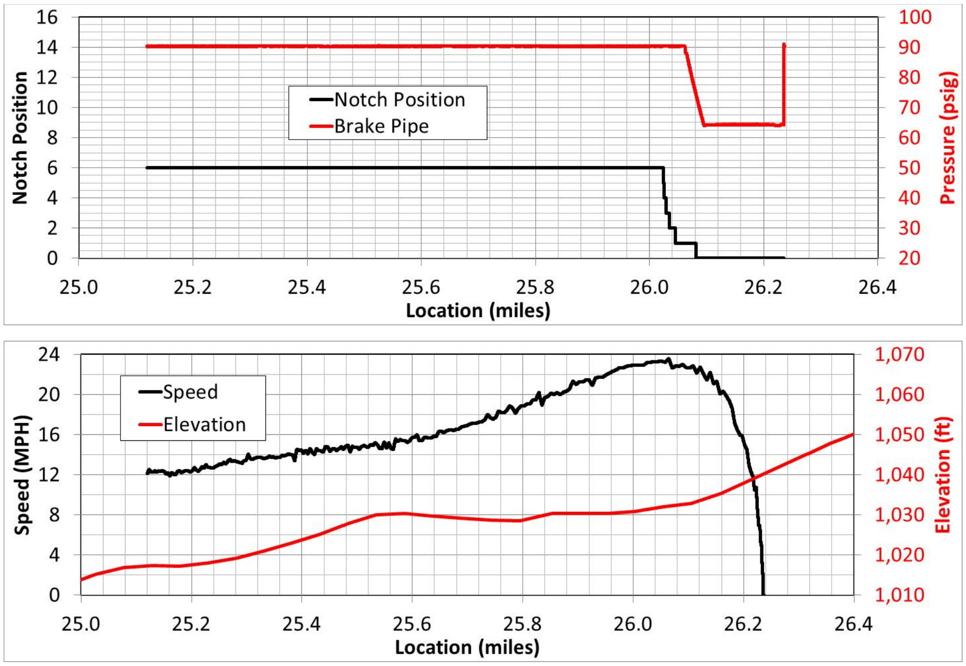

Figure 4-28. Throttle position, brake pipe pressure, train speed and elevation profile, end of day 2 stop

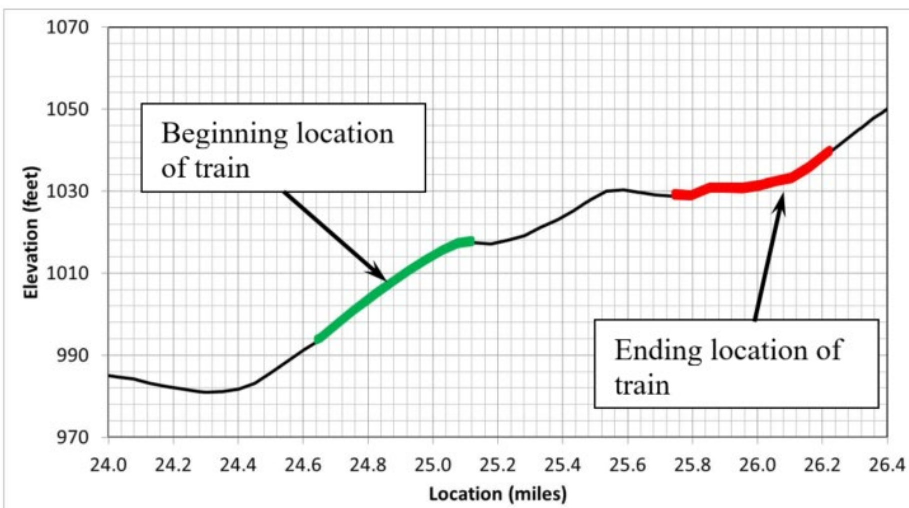

Figure 4-29. Train location on the track profile, end of day 2 stop

Train Speed

The TEDS speed prediction is compared to the measured speed in Figure 4-30. The speed profile predicted by TEDS never diverges from the measured speed profile by more than 2 mph, meeting the acceptance criterion.

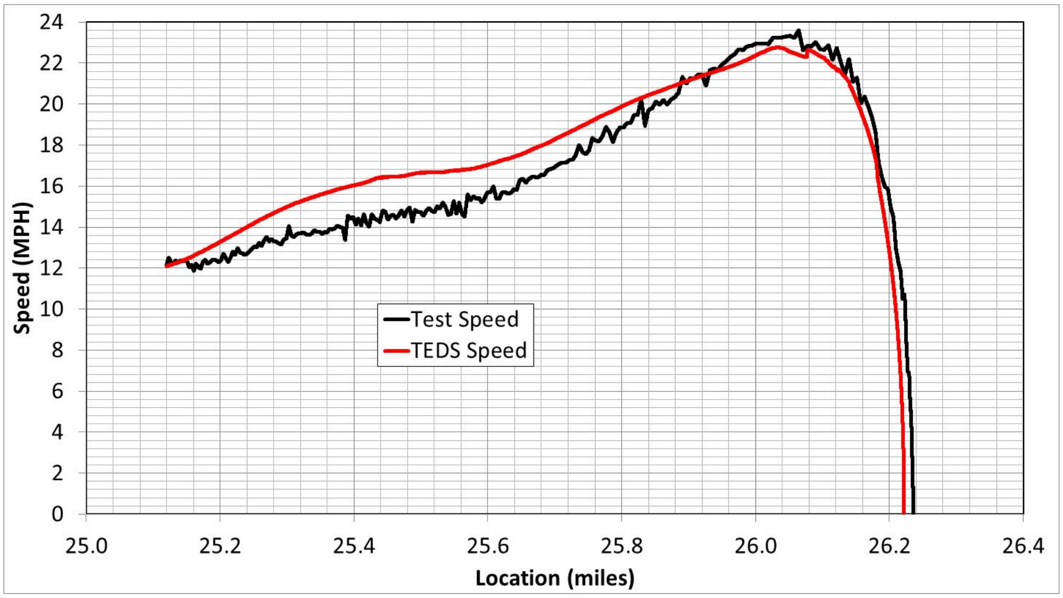

Figure 4-30. Measured and predicted train speeds, end of day 2 stop

Brake Pipe and Brake Cylinder Pressures

The comparison of the measured and predicted brake system pressures on the three test cars is shown in Figure 4-31, Figure 4-32, and Figure 4-33. The predicted brake pipe pressures on all three test cars match the measured brake pipe pressures very well. The slopes of all trends also match, and the steady state pressures—when each test car reaches the application amount—agree with measured data well within the acceptance criterion of 5 psi. Likewise, the final steady state pressures of the brake cylinders also match the measured values within the acceptance criterion, and the slopes of the application and release match those of the measured data very well.

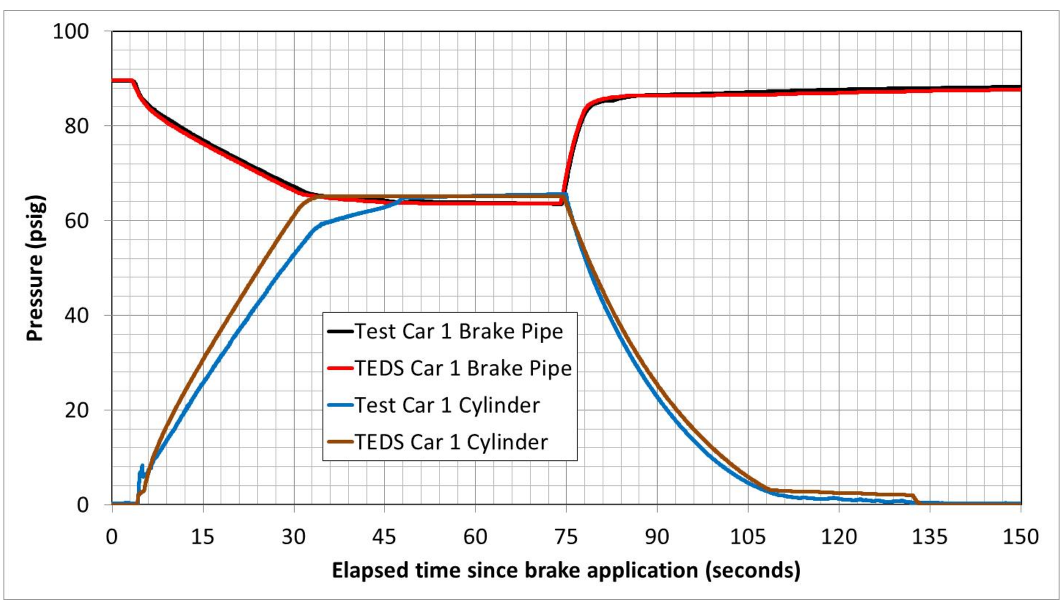

Figure 4-31. Comparison of measured and predicted brake pipe and cylinder pressures on Test Car #1, end of day 2 stop

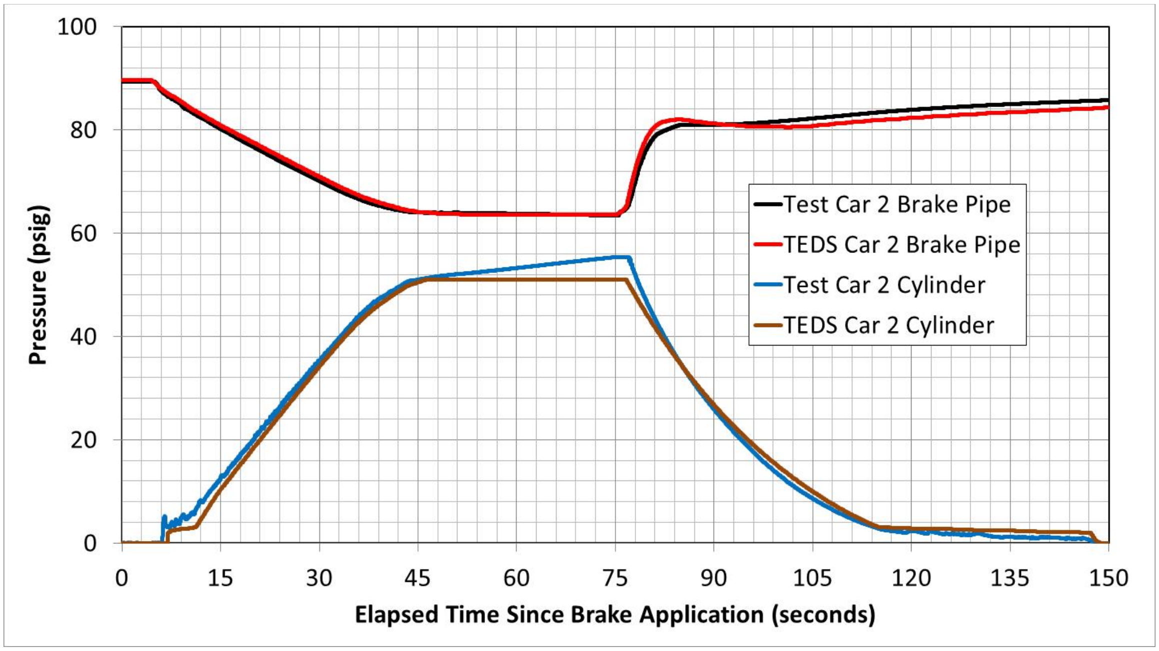

Figure 4-32. Comparison of measured and predicted brake pipe and cylinder pressures on Test Car #2, end of day 2 stop

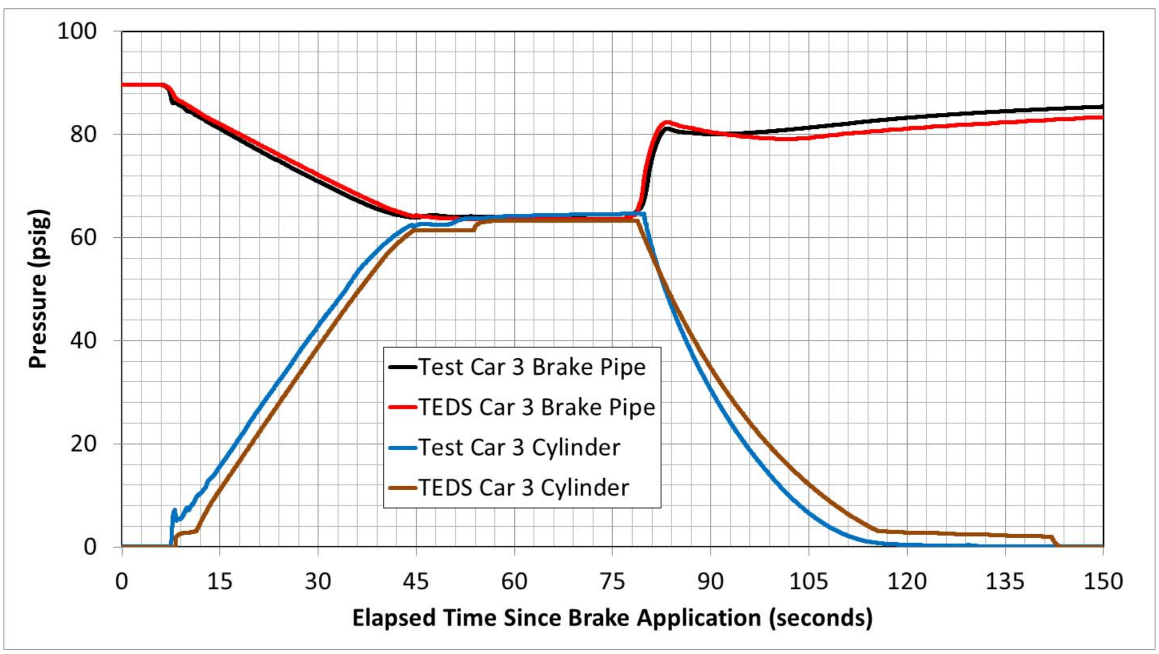

Figure 4-33. Comparison of measured and predicted brake pipe and cylinder pressures on Test Car #3, end of day 2 stop

5 Conclusion

From June 12, 2013, to July 31, 2017, SA developed the TEDS simulation software under contract from FRA. A revenue service validation test of TEDS was conducted over 2 days on a mixed train of 54 loaded cars with a remote locomotive unit (distributed power) operation. There were two locomotives in the lead consist and one active locomotive in the remote consist.

Seventeen cars were cut out of the train at the end of the first test day. The test covered typical major train operating scenarios, such as starting a train from a stop and maintaining speed through throttle manipulation and use of automatic air brakes for speed control and train stop.

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

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

Air brake applications, including emergency, were made with the train standing with both the lead and remote locomotive consists acting as brake pipe controllers. This was done to validate the multiple brake pipe controller feature in TEDS.

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

The measured and predicted pressure for brake pipe and brake cylinder was generally within 1 psi, which is well within the acceptance criterion.

Comparisons between measured data and simulation results show TEDS speed predictions were accurate. For a track segment of 2.23 miles with 10 major throttle changes and 1 air brake application, the speed predicted by TEDS differed by less than 1 mph from that measured during the test.

TEDS also predicted the coupler force on this segment for all three test cars to within about 20 kips, which meets the acceptance criterion.

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

6 References

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2. 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.
3. 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 Fail Technical Conference*, October 2012.
4. 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 2015 Joint Rail Conference*, March 2015.

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
AAR	American Association of Railroads
ASME	American Society of Mechanical Engineers
ECP	Electronically Controlled Pneumatic
FRA	Federal Railroad Administration
GPS	Global Positioning System
INRR	Indiana Northeastern Railroad
kips	Kilo Pounds
MU	Multiple Unit
PTC	Positive Train Control
SA	Sharma & Associates, Inc.
TE	Tractive Effort
TEDS	Train Energy and Dynamics Simulator
WILD	Wheel Impact Load Detector