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TRAIN ENERGY AND DYNAMICS SIMULATOR (TEDS) - A STATE-OF-THE-ART LONGITUDINAL TRAIN DYNAMICS SIMULATOR

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ABSTRACT

Train safety and operational efficiency are enhanced by the ability to understand the behavior of trains under varying conditions. Under the direction of the Federal Railroad Administration (FRA), a longitudinal train dynamics and operation simulation software - Train Energy and Dynamics Simulator (TEDS) - has been developed. TEDS is capable of modeling modern train operations and equipment, and is an effective tool for studying train operations safety and performance as affected by equipment, train makeup, train handling, track conditions, operating practices and environmental conditions.

TEDS simulates the dynamics of longitudinal train action and incorporates the dynamic effects of various different types of draft gears and end-of-car cushioning units including mismatched devices coupled together, the transient response of locomotive tractive and dynamic braking effort, as well as a fluid dynamic representation of the air brake system with the capability to model conventional pneumatic and ECP brake systems.

The capabilities of TEDS are described and demonstrated with several examples. The validation effort undertaken is described at both the component and system level. Comparisons of TEDS simulations of impact tests with the test results are shown to verify the draft gear and end-of-car cushioning unit models. The air brake model predictions are verified by comparing brake rack test results to TEDS simulations of braking behavior.

INTRODUCTION

The need to promote and ensure continuous improvements in railroad safety has led the Federal Railroad Administration (FRA) to the development of a Train Energy and Dynamics Simulator (TEDS); a computer program, for performing longitudinal train dynamics simulations. Such simulations offer opportunities for conducting safety and risk evaluations, energy consumption studies, incident investigations, train operation studies, ride quality evaluations, new equipment design and current equipment evaluation. Programs with such capabilities are not commercially available.

TEDS simulates the behavior of the train along the centerline of an ideal track (longitudinal motion); full multi-body representation for vertical and lateral motion is not included.

Inputs for the mathematical representation of the train behavior include train, car, and locomotive parameters, track characteristics, and train handling. Train handling inputs can be stored in a train handling file, entered at the command prompt during a simulation, or passed using a graphical interface that includes a representation of the controls an engineer can manipulate to operate the train (throttle, dynamic, air and independent brakes).

TEDS includes a fluid dynamics model of both the automatic and independent air brake systems, and a nonlinear model of draft gears and end-of-car cushioning units. Each car and locomotive is modeled as a single lumped mass with a longitudinal degree of freedom, allowing simulation of run-in and run-out events since each car has a unique velocity and acceleration.

TEDS allows locomotives to be placed anywhere within the train and can be independently controlled. The distribution of empty and loaded cars can easily be modified. TEDS is modular, so new equipment, such as new or proposed draft gears and end-of-car cushioning units, can be incorporated into the model. The TEDS package also includes graphical user interface-based preprocessors to create and edit train files, track files, and train handling command files. A library of typical cars is provided, as well as the capability to use the results of an UMLER query for a given manifest to quickly create a train. A postprocessor for quick-look plotting is also provided.

Validation of any mathematical model is a key component of the development process and the user acceptability. The response of draft gear and end-of-car cushioning units in impact scenarios calculated in TEDS is compared to test data. The air brake model results are compared to published test data. Finally, some features of TEDS are demonstrated via examples.

A clarification of the term validation is in order. An exact one-to-one correspondence of any model predictions and test data is unrealistic due to simplifying assumptions used in the development of the model and to the natural variations in the input parameters used for the calculations. For example, the metal friction draft gear depends on the frictional force between metal parts. Friction coefficients are known to have a wide range of values, depending on many conditions. To be able to use a mathematical model of a frictional element, a value for the friction must be chosen, which may not necessarily match exactly the characteristics of every friction draft gear. Therefore, we define validation for the purposes of this paper to include three main components:

- The first component is to predict that an event occurred.
- The second component is to match the trend of an event, so that if a force increases in the test data, the predicted force must also increase.
- The third component is to fairly closely predict the magnitude of the event.

MATHEMATICAL MODEL - TRAIN DYNAMICS

In TEDS, the motion of the train is modeled using a second-order differential equation for each vehicle (locomotive and car). The acceleration of each vehicle is obtained from the net force acting on it. The net force includes track grade forces, resistance forces, coupler forces, braking forces (if active), and tractive effort or dynamic braking forces (if the vehicle is a locomotive). Forces acting at the wheel/rail interface are limited to the level that can be sustained by the local value of track adhesion, which can be modified by the user. The acceleration is integrated to obtain the velocity, and the velocity is integrated to obtain the position. The relative positions and velocities between vehicles are then used to update the coupler forces at each end of each vehicle.

The vehicle characteristics required to model the longitudinal behavior of the train along the track include:

- weight
- length
- truck resistance characteristics
- aerodynamic resistance characteristics
- coupling element characteristics
- braking characteristics (for example braking ratio), and
- tractive effort and dynamic braking effort for locomotives.

A library of standard coupling elements (couplers, draft gear and cushioning units) is included in TEDS.

MATHEMATICAL MODEL - AIR BRAKE

The air brake model in TEDS represents the train-length brake pipe and the various control valves and other components at each vehicle that connect to and interact with the brake pipe. The brake pipe model employs an iterative solution to discretized fluid mechanics differential equations (continuity and momentum) to represent the time history of airflow and pressure throughout the pipe. The effects of leakage from the pipe and friction due to airflow within the pipe are included. Control valves are modeled as an interconnected system of reservoirs with flow between them controlled by fixed size orifices. Active flow paths are determined by the logic of the particular valve type. Reservoir pressures are updated based on calculated orifice flow rate and mass conservation principles for valve component volumes. In a similar manner, coupling between the control valve and brake pipe models relies on airflow between the pipe and the various devices connected to it.

This modular approach permits the simulation of any type of control valve at any location along the brake pipe, so the brake systems of multi-platform cars can be easily modeled. Brake valves may also be located anywhere in the train, allowing simulation of distributed braking, such as in distributed power systems and two-way end-of-train and mid-train devices. TEDS includes models for control valve types ABDX, ABDXL, DB60, DB60-L, ABDW, ABD, AB, and 26-F, as well as for A-1 and emergency vent valves, and empty/load valves.

Electronically controlled pneumatic (ECP) brakes are also represented in the TEDS air brake model. In a train equipped with ECP brakes the application and release signal is communicated electronically. All control valves in the train receive the brake application/release signal simultaneously. In addition, the brake cylinder pressure at each car is individually controlled based on the car’s loading and braking characteristics to obtain a uniform deceleration rate for all the cars in the train. Other significant ECP brake system features, such as graduated release, rapid cylinder pressure build-up rate, and continuous reservoir charging (even while brakes are applied), are also simulated in TEDS.

TRACK INPUTS

The track features required to model the train behavior include elevation to obtain grade forces and curvature to calculate curving resistance forces. The track must be defined with sufficient length to locate the entire train for the duration of the simulation. Track is defined using a series of records indexed by a position value in ascending order. Thus a user may choose to define a track using either absolute footage values or relative position values (by choosing a particular footage as the starting point – 0.0 feet). For each record, elevation, curvature and superelevation values must be defined. The train can be oriented and run in either direction on a track.

TRAIN INPUTS

The train features required for simulation include number of locomotives and cars, their respective lading conditions, and the type and specific characteristics of each vehicle. These can be defined quickly using the Graphical User Interface (GUI). TEDS has a library of the most prevalent cars in use in North America as well as a capability to import data from UMLER to generate custom cars and trains from a train manifest. Custom throttle characteristics can also be created for use in locomotive definition. Multiple locomotive consists can be defined with this interface as well.

TRAIN HANDLING INPUTS

TEDS conducts a train simulation using a series of commands. There are four categories of commands:

- Initialization,
- Simulation controls,
- Throttle & Dynamic Braking controls, and
- Air Braking controls.

These commands provide a user full control on how the simulation is conducted (output frequency, vehicles monitored, saved intermediate states, etc.) as well as how a train is operated on a track (throttle, dynamic and air braking).

GRAPHICAL USER INTERFACE

TEDS has a rich GUI providing a convenient tool set for pre-processing input data, simulating trains and post-processing simulation results. Pre-processing tools include dialogs for creating various input data such as track, vehicle, train, and train handling. Simulation tools include three different modes of running simulations – command-mode, graphical-mode, and batch-mode. Post-processing tools include a data plotter, a simulation animator, and a data extraction utility.

Figure 1 shows the main GUI dialog that is displayed when TEDS is launched. From this dialog users can load projects, launch pre-processor dialogs, launch simulators in different modes, as well as launch post-processor dialogs. Figure 2 shows the ‘Track Editor’ dialog wherein users can define the track, one record at a time, or by importing data from comma-delimited (CSV) files. Track data can also be exported to CSV files as well as plotted for a quick check. Basic validation of track data is provided to ensure track meets most North American track limits. Warning messages are issued when track characteristics falls outside these limits. Figure 3 shows the ‘Vehicle Library’ dialog wherein users can view standard vehicles (provided with TEDS), as well as create custom vehicles as necessary. Figure 4 shows the ‘Train Editor’ dialog that allows users to create train consists. Vehicle length and tare weight can be adjusted and lading can be defined for vehicles in the train. Individual and Range editing modes, as well as the ability to reverse the vehicle order in a train, allow users to quickly define a train consist as necessary. Figure 5 shows the ‘Handling Editor’ dialog wherein users can define a set of simulation and train handling commands. The available run-mode commands are listed on the left pane for users to select. Once selected, the dialog guides users on how to complete that command by listing the acceptable arguments.

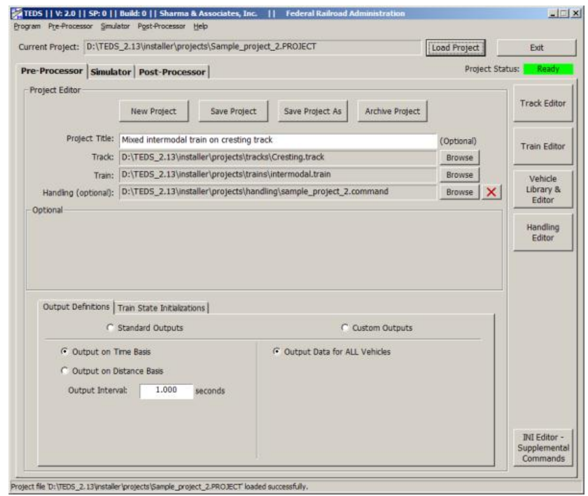

Figure 1. TEDS main dialog.

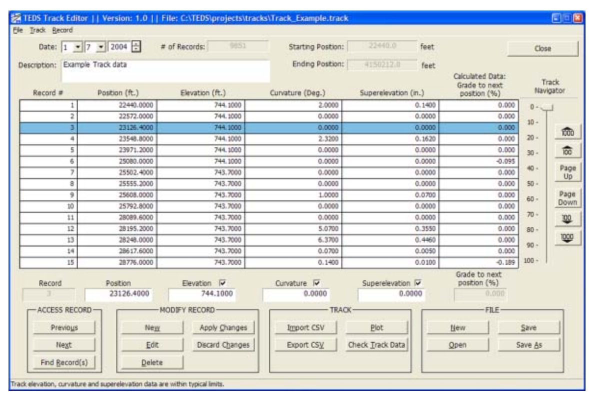
Figure 2. TEDS Track Editor.

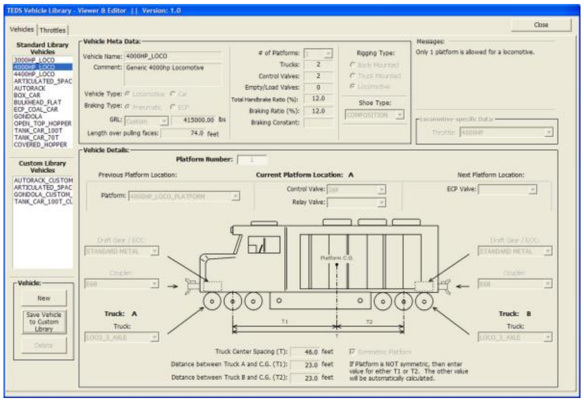

Figure 3. TEDS Vehicle Library.

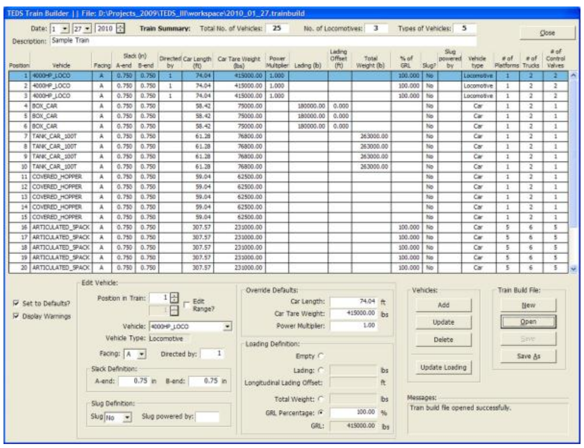

Figure 4. TEDS Train Editor.

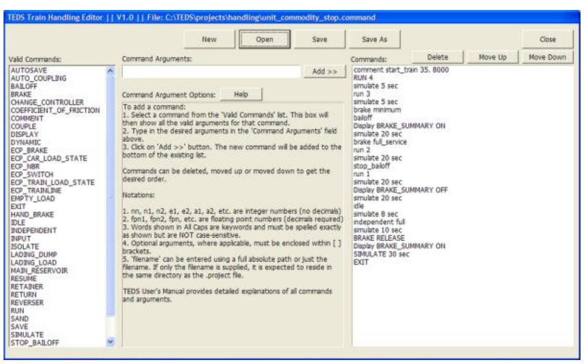

Figure 5. TEDS Handling Editor.

Figure 6 shows the 'Simulator' tab of the main GUI that allows for launching the TEDS simulator in various modes. In the lower half of the dialog, a batch of simulations can be created. This allows users to run numerous simulation studies without intervention. Figure 7 shows the 'Data Plotter' dialog that allows quick plotting of various output data with a basic level of control on line color, line type and axes scaling. Figure 8 illustrates the 'Simulation Animator' module that allows users to replay completed simulations at various animation speeds to analyze particular events. The Animator depicts the train on the simulated track with a dynamic representation of various output parameters, such as coupler forces, brake cylinder pressures, etc., with their magnitude indicated either by color (as shown in Fig. 8) or in an optional bar chart format.

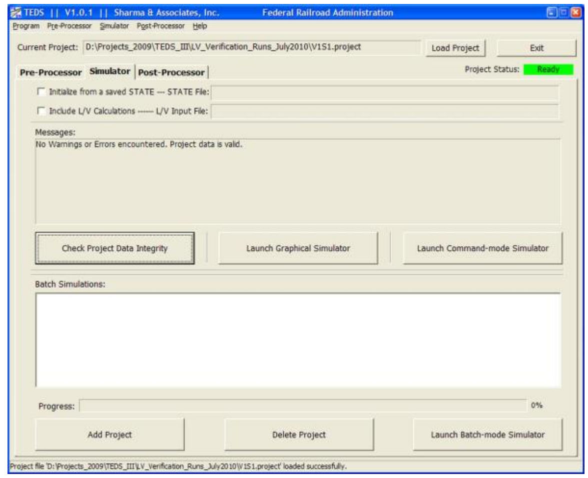

Figure 6. TEDS Simulator tab.

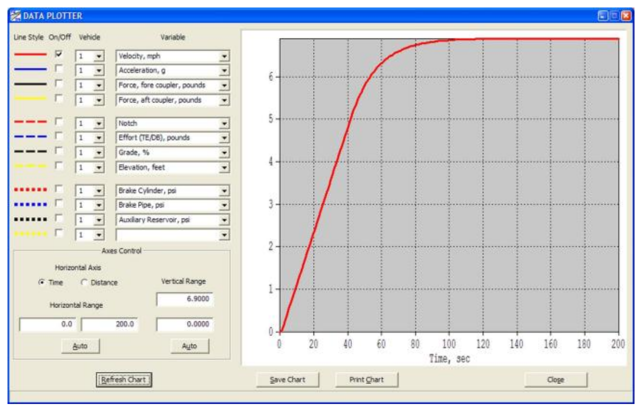

Figure 7. TEDS Data Plotter.

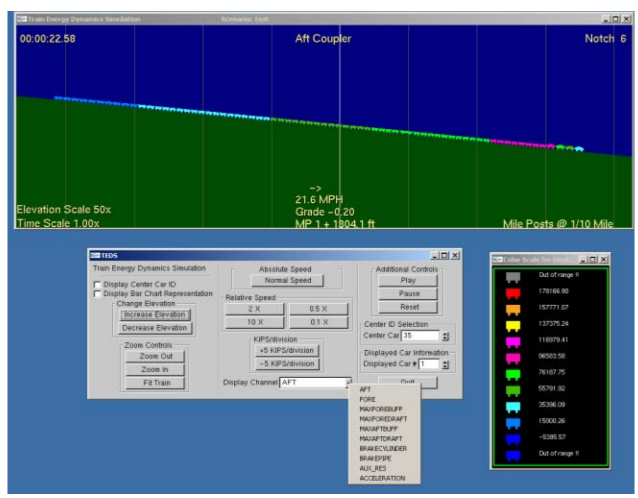

Figure 8. TEDS Simulation Animator.

DRAFT GEAR MODEL VALIDATION

Impact testing was conducted by Sharma & Associates to validate the performance of the mathematical model of the draft gear. These tests were performed at several different impact speeds. Force was measured with an instrumented coupler installed on the anvil car backed up by two loaded cars with hand brakes applied. The impact speed of the hammer car was controlled by releasing it from various heights along a ramp. For impact scenarios, the first peak is the critical one to match. It should also be noted that test results are not always necessarily repeatable, whereas model predictions always produce the same results.

Figure 9 shows the TEDS draft gear module predicted peak force compared to the impact test data for an M-901E gear at nine (9) different impact speeds. The speeds tested were 3 through 7 mph at 1/2 mph increments. The comparison shows the TEDS predictions match fairly well to the controlled test data.

A comparison of test data with TEDS predictions for end-of-car cushioning units are shown in Figure 10. The results are reasonable given normal variations in performance of the unit.

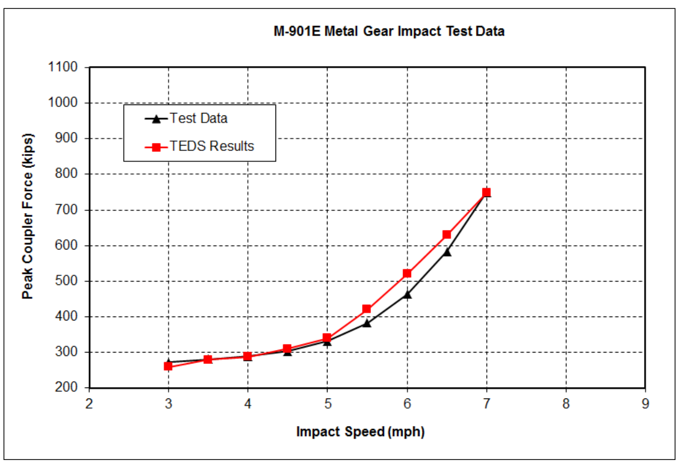

Figure 9. Comparison of TEDS predictions with impact test data for an M-901E metal draft gear at several impact speeds.

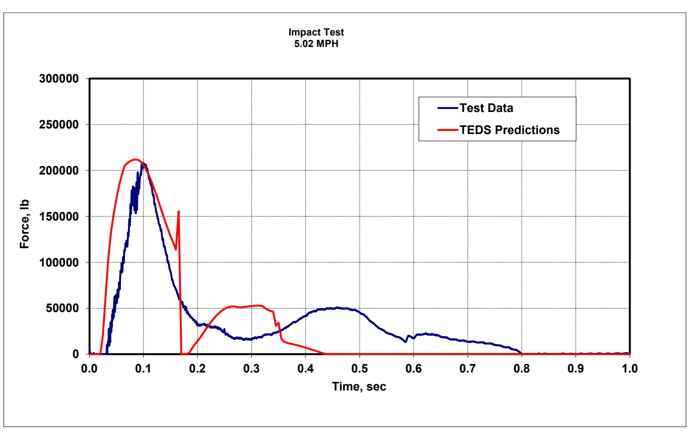

Figure 10. Comparison of TEDS predictions with impact test data for a 50,000 pound preloaded end-of-car cushioning unit at 5 mph.

AIR BRAKE MODEL VALIDATION

Characteristics representing the particular behavior of the brake pipe and various valve types were developed based on pressure time histories of the brake system components during train brake operation (e.g. application, release and charging). This information was obtained from published literature and from data collected with a single car test fixture. Published sources include air brake test rack data from ASME and Air Brake Association proceedings, performance and testing specifications from AAR Standards and Recommended Practices (S-461, S-464, and S-466), and descriptions from air brake manufacturers' instructional brochures and maintenance documents. The test fixture incorporated a single car set of air brake components, including control valve, combined auxiliary/emergency reservoir, and equivalent volumes for brake cylinder and brake pipe, instrumented with pressure transducers and a PC-based data collection system (Figure 11).

Figure 11. Single-car brake system test fixture for control valve characterization

During the development phase, to verify the air brake model functionality, these published and collected data were used to check the model's formulation and integrity of results. In particular, TEDS was used to simulate various air brake test rack cases. An example case involving a test rack simulation of a 50-car train is shown in Figure 12. The published test rack data is reproduced from Ref [1] and displayed along with the TEDS predicted results. The brake pipe and brake cylinder pressures at Car 1, Car 25 and Car 50 are used for comparison. The close correspondence between test rack data and TEDS simulation output shown in this example is typical of the TEDS air brake model predictions.

The ECP brake model functionality in TEDS was developed and verified using published data, descriptions, and the AAR S-4200 specification for ECP brake equipment. For example, Figure 13 compares TEDS simulated ECP brake system behavior with published test data, Ref [2], from an existing revenue train equipped with ECP brakes. Brake pipe, cylinder and supply reservoir (combined auxiliary and emergency) reservoir pressures at the first and last cars are shown for several cycles of full service brake application and release. Brake pipe charging has been cut out to demonstrate the capacity of the supply reservoirs, so the pressure distribution is flat and the response at each car throughout the train is essentially identical. These comparisons show that TEDS accurately represents ECP characteristics, such as cylinder pressure build-up and release rates, supply reservoir and brake pipe response.

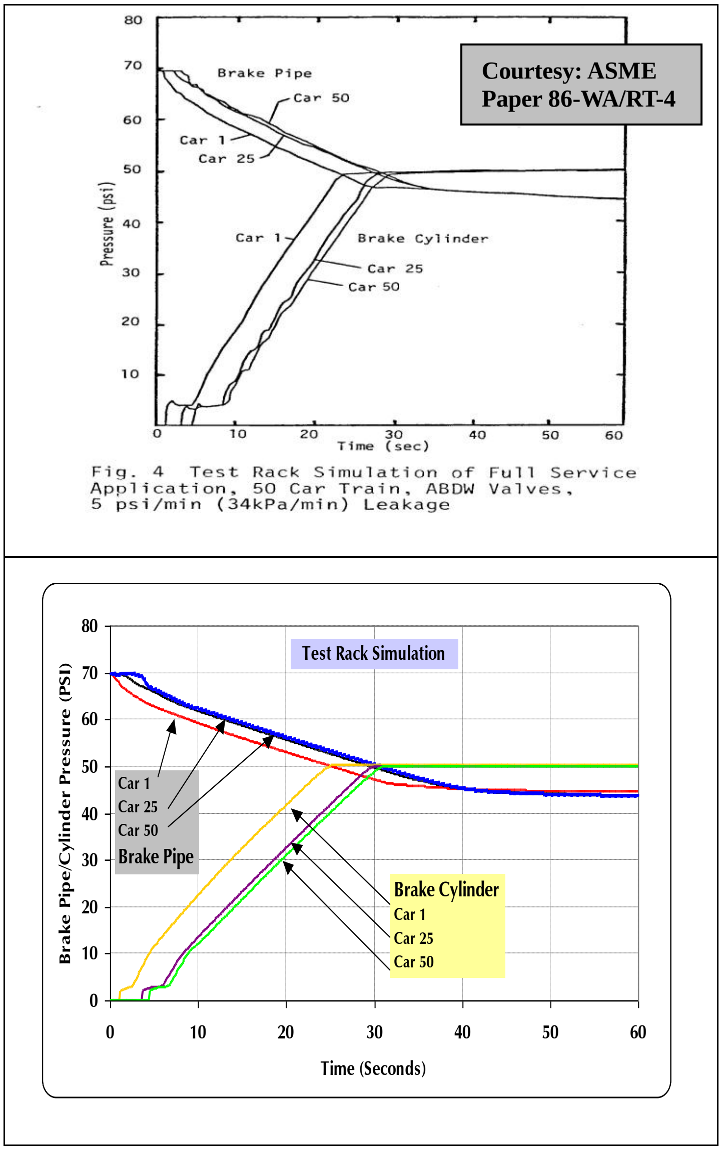

Figure 12. Comparison of TEDS air brake model predictions with published test rack data for a 50-car train

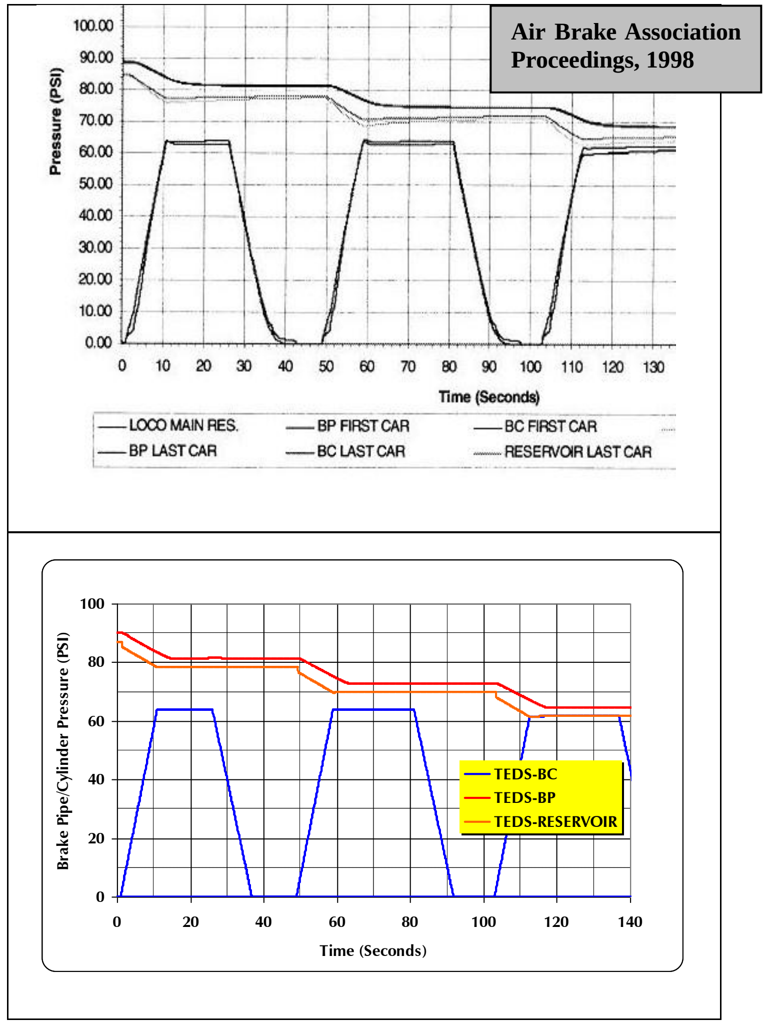

Figure 13. Comparison of TEDS air brake model predictions with published data for cycle braking in a revenue train equipped with ECP brakes [2].

TEDS FEATURES

TEDS includes several advanced features including:

- Mismatched coupling elements to capture transients that depend on the type of elements present in a connection
- Multiple train consists with independent control to allow simulation of train separation and the instant of impact (not collisions with the attendant plastic deformation of car or locomotive structural components)
- ECP brakes
- Rich graphical interface

The following highlights the first two of these features.

Mismatched elements

An impact scenario is simulated with five hopper cars as anvils and three hammer cars. The anvil car furthest from the impact location has the hand brakes fully applied. The three hammer cars are begun on a 10 percent grade incline and reach about 5 mph at the instant of the impact. Three different cases are considered: the first with a matched pair of metal draft gears on both couplers in the impact connection; the second with one metal draft gear and one 100-kip preloaded end-of-car cushioning unit with 15 inches of stroke; and the third with matched 100-kip preloaded end-of-car cushioning units.

Figure 14 shows the time history of these three scenarios. Both the mismatched connection and the matched EOC connection show about half the peak force developed as that in the matched gear scenario. The matched EOC and mismatched scenarios show about the same force, which is an indication that the energy dissipation in the EOC with its longer stroke than the draft gear reduces the peak force in the connection, even when mated to a draft gear with one-fifth of its stroke. The addition of a second EOC to the connection further reduces the peak force at initial impact, but not significantly.

The multiple peaks shown in Figure 14 for the matched draft gears are due to the impact of each successive car in the hammer cut. It should be noted that force values are depicted as negative values to indicate compressive nature.

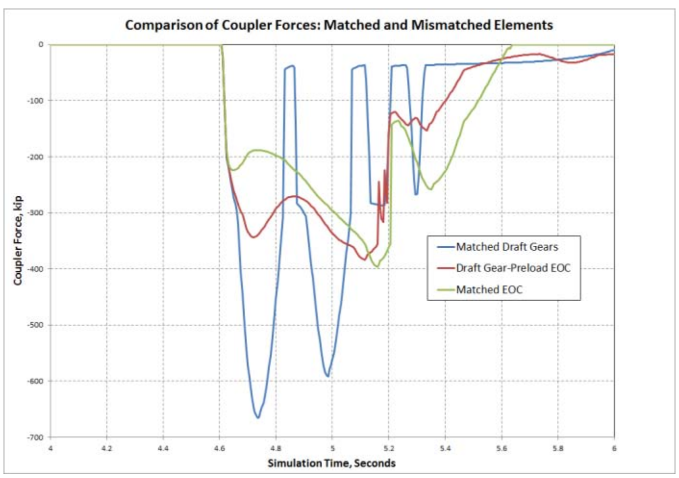

Figure 14. Comparison of TEDS predictions of coupler forces in matched and mismatched connections.

Multiple Trains

This scenario demonstrates the simultaneous operation of multiple trains on a single track. Two simple trains consisting of one locomotive and nine cars each were simulated using TEDS. The leading train was placed in throttle and advanced for a short period before starting the following train. The speeds of the two trains are shown in Figure 15, along with the throttle position used to independently control the locomotive of each train. The separate speed curves clearly show that the trains are operating independently and are separating.

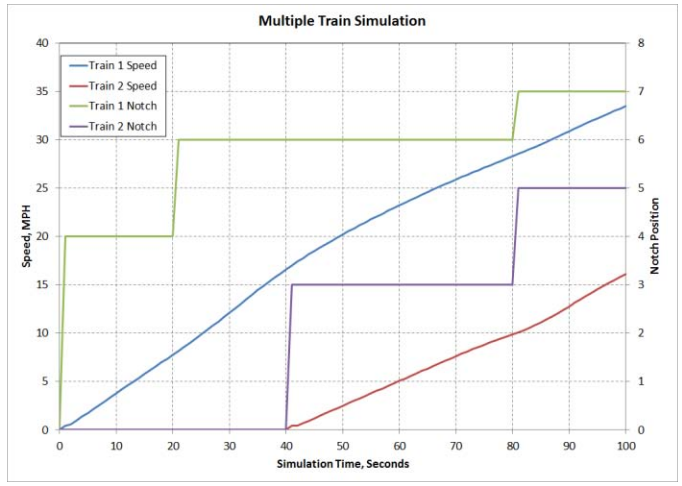

Figure 15. Comparison of speed of two trains simulated simultaneously. The locomotive notch position of each train is also shown.

CONCLUSIONS

A new computer program for simulating the longitudinal behavior of one or more trains has been developed. The program has up-to-date capability to model a wide range of railroad equipment and operations, including Distributed/remote power, Electronically Controlled Pneumatic (ECP) brakes, modern brake valves, modern coupling systems including M-901G draft gears and cushion units with an active draft stroke, etc. Several features of this model were demonstrated.

Preliminary validation of key components/systems has been successfully completed, and initial demonstrations have shown that the program can effectively model expected train performance in a variety of scenarios.

TEDS will improve FRA and the industry's capabilities to study train dynamics and will thus reduce risks, as well as improve the safety and performance of train operations.

ACKNOWLEDGMENTS

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2. McLaughlin, Bryan, "ECP Brake's First Stand-Alone Test Train," Air Brake Association Proceedings, September, 1998.

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ABSTRACT

The Train Energy and Dynamics Simulator (TEDS) is state-of-the-art simulation software, developed by the Federal Railroad Administration (FRA), to study train operation safety and performance as affected by a wide variety of rolling stock, track, train handling and operating configurations. As part of developing TEDS, existing and published data on braking, draft systems and train performance were used for initial validation of TEDS.

This paper describes two revenue service tests conducted to further validate TEDS. The first test was on a loaded unit train, while the second test was on a mixed train with empty and loaded cars and included distributed power in which the remote brake valve was cut in. Collected test data included throttle position, train speed, locomotive power, brake system pressures and coupler forces. Several events from these tests, representing typical train operating scenarios, were selected for comparison with TEDS predicted results. The TEDS predictions matched the measured test data for all of the scenarios simulated, further validating the performance of the software and offering additional assurance on the use of TEDS for simulating performance and safety critical train dynamic behavior.

INTRODUCTION

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 sufficient number of scenarios to establish confidence in the simulator predictions. Previous validation of TEDS [1, 2] included subsystem validation of the air brake model and the draft gear model using published data. Train speed predictions were validated using published event recorder data for several incidents investigated by the National Transportation Safety Board (NTSB). The current effort adds to this previous validation work that was completed for TEDS [1, 2].

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 (coupler force, brake pipe and brake cylinder pressure, train 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 predicted by TEDS should agree with measured coupler force data to within 20% (significant peaks are those greater than 100,000 lbs.). This criterion provides a reasonable fit to the variations in coupler force seen in the draft gear impact test data [3].
   - For steady state (equalized) brake cylinder and brake pipe pressures, TEDS predictions and measured data should agree within 5 psi. This variance is comparable to the Association of American Railroads' (AAR) certification requirements for brake cylinder pressure gauges on the single car test rig, where equalized cylinder pressure is allowed a ±3 psi variation from the target (S-486, paragraph 2.3.4), [4]. However, during transient phases (i.e. when the brakes are being applied or released) it is acceptable for the difference

between TEDS predictions and measured data to be greater than 5 psi for brief periods.

- Predicted and measured train speed should agree within 2 mph at any given time. One of the basic validation criteria is that the predicted and measured train speeds should closely 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 as a function of time.

Predicting the magnitudes of the event's parameters of interest (criterion 3) is the most difficult criterion to satisfy due to the simplifying assumptions used to develop the model and the need to 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 physical measurements.

For all simulations, no special "tuning" or adjustments to the nominal model parameters were made in order to make the match to the test data. Only adjustments to parameters that are variables in the library vehicle definitions were made, and only as needed to more closely match. For example, brake cylinder piston travel adjustments to test car #2 were made since the test data showed this car had a lower steady-state brake cylinder pressure than the other two test cars.

TEST SCOPE

The validation effort consisted of collecting train performance data from two operating revenue trains, identifying appropriate events to be used in the validation, simulating those events using TEDS, and, finally, 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 runout tests were also conducted.

TRACK PROFILE

Both the unit train and mixed train revenue service tests were conducted on the track profile shown in Figure 1. The unit train was operated in the decreasing MP direction, while the mixed train was operated in the increasing MP direction.

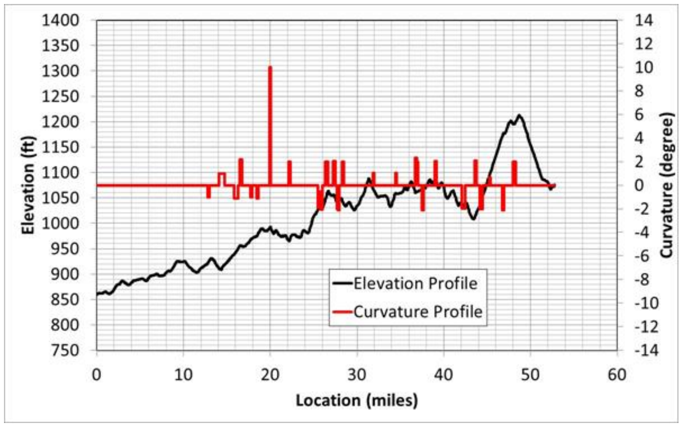

Figure 1. Track Profile of Test Route.

UNIT TRAIN - CONFIGURATION

The unit test train was made of 4 locomotives and 85 loaded cars as listed below:

- 3 active locomotives (3000, 2250, 2250 HP)
- 1 locomotive dead-in-tow (for contingency)
- Test Car #1 loaded 263,000 lb. open top (gravel) car
- 42 loaded 286,000 lb., covered hopper cars
- Test Car #2 loaded 263,000 lb. open top (gravel) car
- 21 loaded 286,000 lb., covered hopper cars
- Test Car #3 loaded 263,000 lb. open top (gravel) car
- 21 loaded 286,000 lb., covered hopper cars

The overall train characteristics are:

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

The covered hopper car weights are based on the tare and gross load stenciled on the cars. The vehicle lengths are based on measurements taken on representative cars. The distribution of vehicle weights and lengths are shown in Figures 2 and 3, respectively.

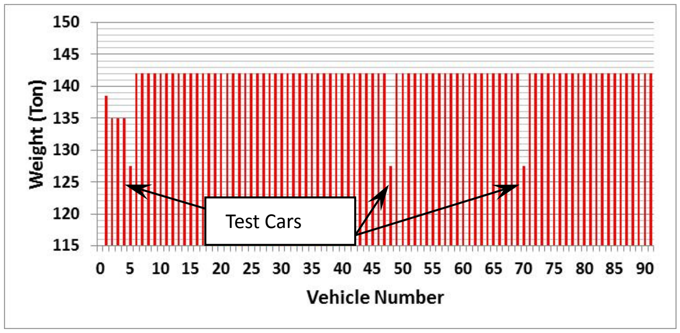

Figure 2. Unit test train vehicle weight distribution.

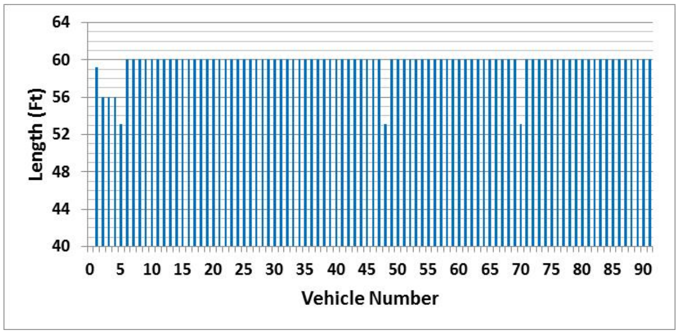

Figure 3. Unit test train vehicle length distribution.

UNIT TRAIN - INSTRUMENTATION

Each of the test cars was equipped with a SoMat eDAQ*lite* data acquisition system. A dynamometer coupler was installed on each of the test cars, along with pressure transducers to capture brake pipe, brake cylinder, and auxiliary reservoir pressure. Additionally, the SoMat on Test Car #1 collected traction motor volts and amps on the #2 motor on each of the (active) locomotives, along with the throttle position. Equalizing reservoir pressure was also monitored. These locomotives are not equipped with dynamic braking.

All measurements were recorded at 200 samples/second, except for the GPS measurements for locomotive speed, which were collected at 1 sample/second. TEDS results are reported at 10 samples/sec.

Train speed was obtained by calculating the differences in GPS position. This was done within the GPS module. The GPS module for the SoMat was a Garmin GPS 18x. No event recorder speed was available for either of the validation tests.

The pressure transducers had an accuracy of ±2% full scale (FS). There were three ranges of pressure transducer included in the testing: 0-100 psig, 0-150 psig, and 0-200 psig. Thus the accuracy of these transducers is ±2 psig, ±3 psig, and ±4 psig, respectively. The dynamometer couplers with full-scale limit of 1,000,000 lbs. have an accuracy of ±10 kips

UNIT TRAIN - STARTUP AND SPEED CONTROL

The unit 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. The large magnitude drops in the brake pipe pressure shown in Figure 4 between mile 5 and 5.5 are not physical, and are likely due to transducer signal dropout.

The measured speed is compared to the speed predicted by TEDS in Figure 5. 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 the introduction.

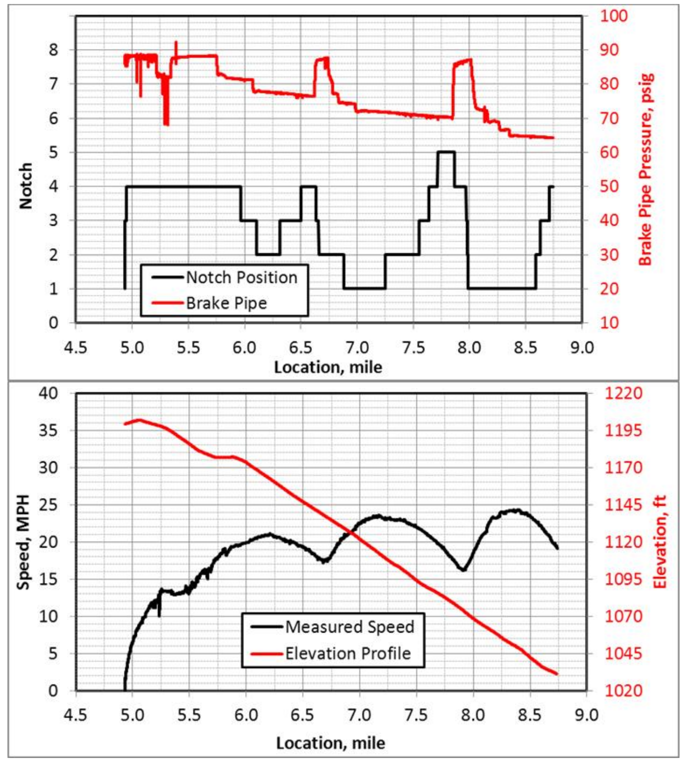

Figure 4. Unit train handling and elevation profile for startup and speed control event.

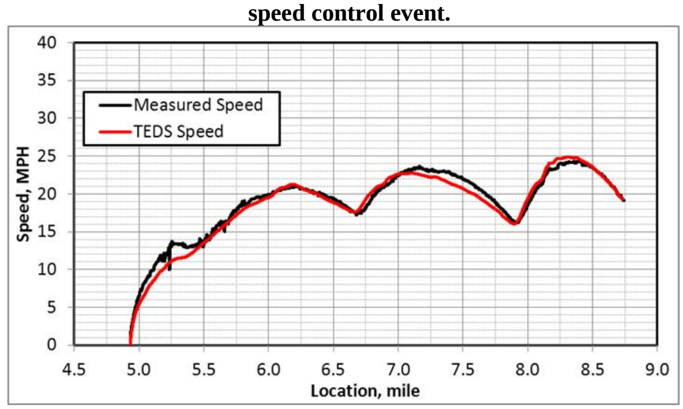

Figure 5. Comparison of measured and TEDS predicted speed Unit train - Startup and speed control event.

Finally, Figure 6 shows the comparison of the pressures on Test Car #2 predicted by TEDS with the measured test data. The match is excellent, again meeting the validation criteria outlined earlier. The stair-step characteristic seen in the TEDS brake cylinder pressure buildup results from the control valve cycling between the applied and lap positions. This typically occurs when the brake pipe pressure is reducing slowly. The insufficient recharge between releases is also evident in Figure 6, since the brake pipe pressure continues to drop with each subsequent application.

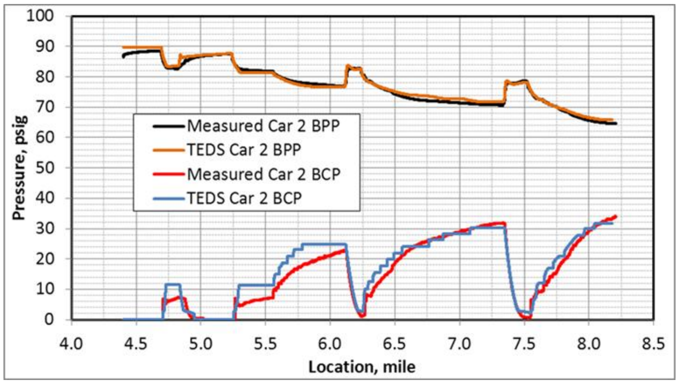

Figure 6. Comparison of TEDS predicted and measured pressures on Test Car #2.

UNIT TRAIN - BUNCHING AND RUNOUT

The second event to be considered consists of a reverse move to bunch the train, followed by a runout. Figure 7 shows the elevation profile for this event. Figure 8 shows the train handling utilized. The train was bunched and accelerated to about 5 mph in reverse, at which point the throttle was wiped to idle and the independent brake was applied. This caused the train cars to runout generating high draft force spikes in the draft gear and couplers. The train then decelerated to a stop.

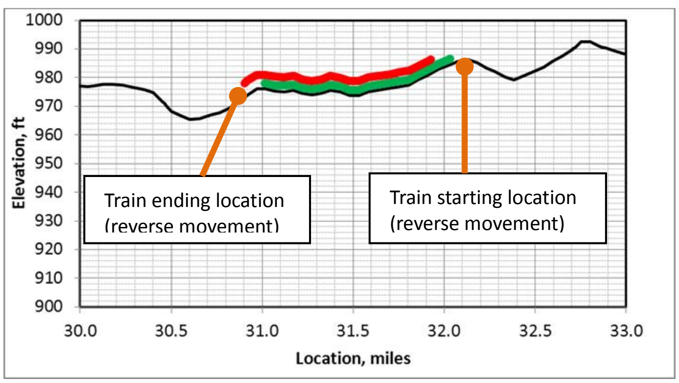

Figure 7. Elevation profile for Unit train bunching and runout event.

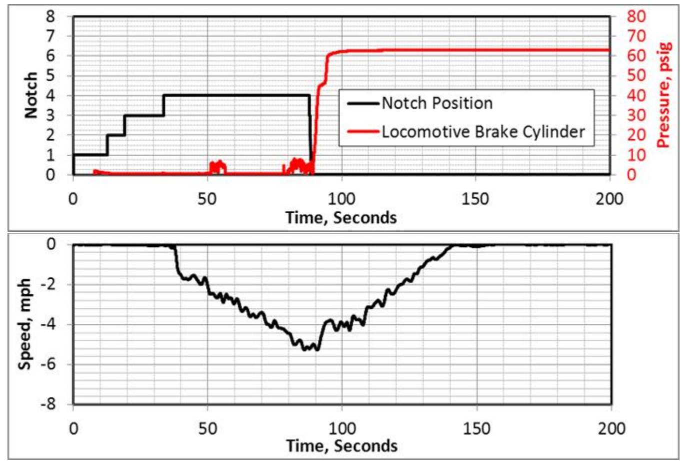

Figure 8. Train handling for Unit train bunching and runout event.

Figure 9 shows the comparison of the train speed predicted by TEDS with the measured train speed. The match is excellent except for the initial portion at low speed. The lag in the measured speed response upon train start-up is due to internal filtering of the computed speed signal in the GPS device used for measuring train speed. At higher speeds the slope of the trends match well, meaning that the accelerations were also accurately predicted.

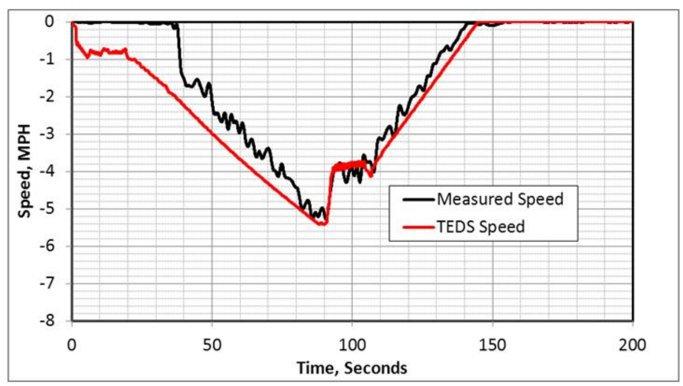

Figure 9. Comparison of predicted and measured train speed for Unit train bunching and runout event.

The comparison of predicted and measured coupler force is shown in Figure 10 for Test Car #2 and in Figure 11 for Test Car #3. Test Car #3 had the highest coupler force (200 kips) of all three test cars for this event. The predicted coupler force matches test data well in both magnitude and timing for both test cars, meeting all three validation criteria laid out in the introduction. Both the steady force levels and the dynamic run-out event were accurately simulated.

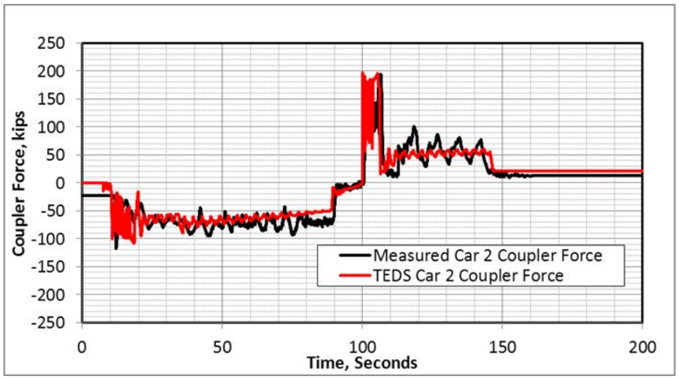

Figure 10. Comparison of coupler force on Test Car #2 for the Unit train bunching and runout event.

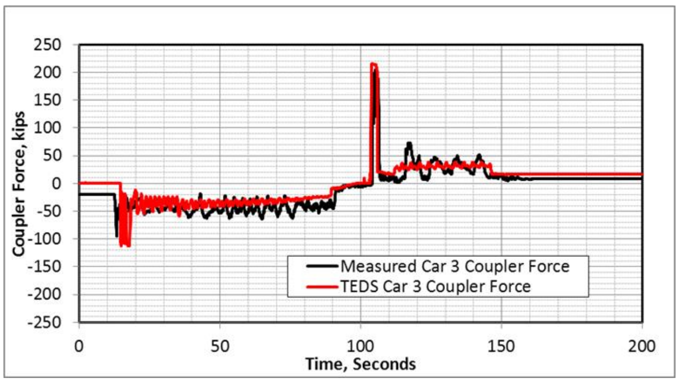

Figure 11. Comparison of coupler force on Test Car #3 for the unit train bunching and runout event.

MIXED TRAIN - CONFIGURATION

The test train was made of 61 vehicles as listed below:

- 2 active locomotives (3000, 2250 HP)
- Test Car #1 (loaded gravel car)
- 33 mixed cars (22 loaded 11 empty)
- Test Car #2 (loaded gravel car)
- 21 mixed cars (3 loaded and 18 empty)
- Test Car #3 (loaded gravel car)
- 1 active locomotive (2250 HP); 1 locomotive dead-in-tow

The overall train characteristics are:

- 7,500 HP
- 4,596 trailing tons
- 3,495 feet total length

The vehicle lengths and tare weights were obtained from measurements and capturing the tare weight stenciling. The distribution of vehicle weights and lengths throughout the train are shown in Figures 12 and 13, respectively.

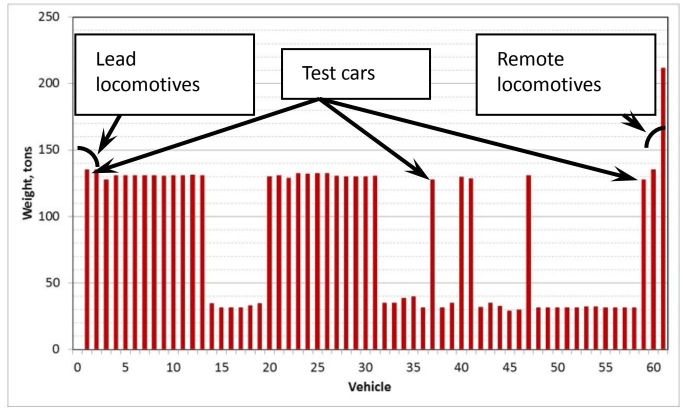

Figure 12. Mixed train car weight distribution.

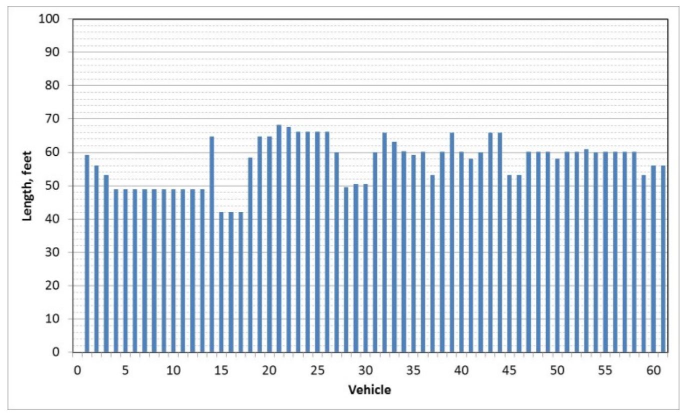

Figure 13. Mixed train car length distribution.

MIXED TRAIN - INSTRUMENTATION

Instrumentation and sample rates used on the mixed train were identical to those on the unit train with the addition of traction motor volts and amps on the #2 motor of the remote locomotive collected on the SoMat on Test Car #3.

MIXED TRAIN - FULL SERVICE AND EMERGENCY

With the train stationary, full service and emergency brake applications were initiated from both ends of the train to validate the multiple brake pipe controller feature in TEDS. Radio voice communication between the lead and remote locomotive engineers allowed for synchronizing brake applications.

The event began with a full service reduction, followed by a release. Shortly afterward, an engineer-initiated emergency was applied, again from both ends of the train simultaneously, followed by a release. Figure 14 shows the trend of the brake pipe pressure for this event on Test Car #1. Figure 15 shows the corresponding brake cylinder pressure on Test Car #1. The match between predictions and test data is excellent for both brake pipe and brake cylinder pressures. Figures 16 and 17 show the brake pipe and brake cylinder pressures at Test Car #3 for this event. Both of these also show a good match between TEDS predictions and test data.

In each of these air braking cases, the TEDS predictions match the test data to well within the established validation criteria. The results from this braking event demonstrate the validity of TEDS to simulate air braking with multiple brake valves, as is used in distributed power operations.

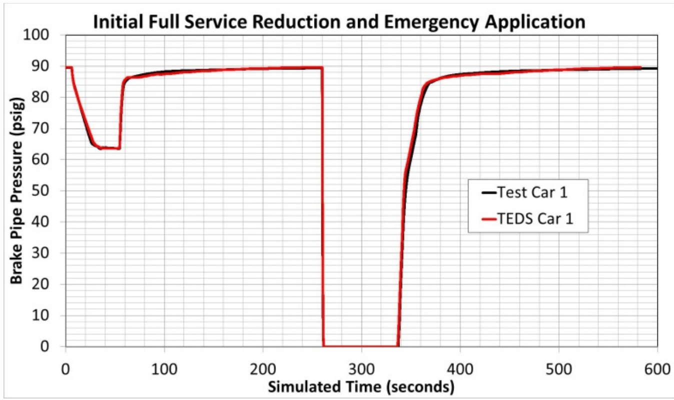

Figure 14. Test Car #1 brake pipe pressure for the mixed train braking test.

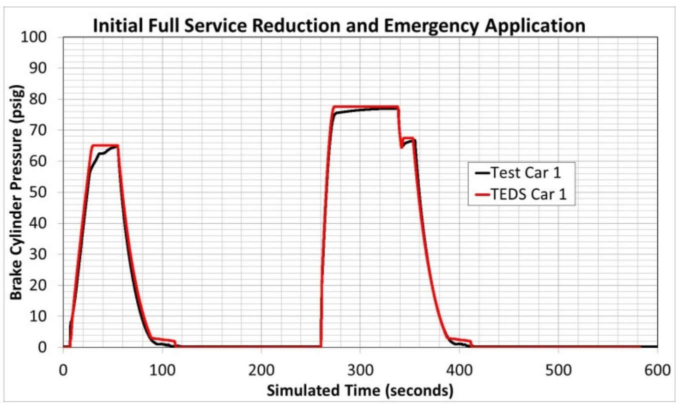

Figure 15. Test Car #1 brake cylinder pressure for the mixed train braking test.

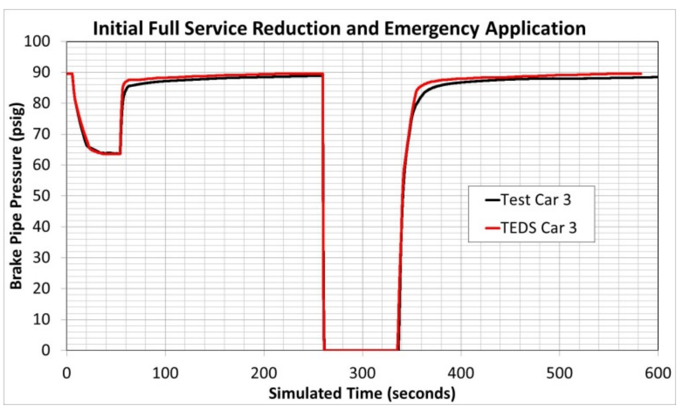

Figure 16. Test Car #3 brake pipe pressure for the mixed train braking test.

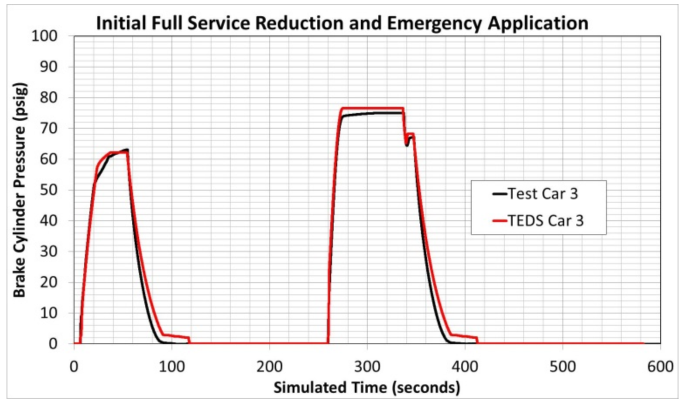

Figure 17. Test Car #3 brake cylinder pressure for the mixed train braking test.

MIXED TRAIN - STARTUP AND STOP

This event involved the mixed train starting up from zero speed, accelerating to about 12 mph, negotiating undulating terrain, and then braking to a stop. Locations of the train, on the track profile, at the beginning and end of the event are shown in Figure 18. The train handling, throttle notch position and brake pipe pressure throughout the event, is shown in Figure 19. Figure 20 shows the measured train speed overlaid on the track elevation profile. The brake pipe was controlled from the head end only; the brake pipe at the remote locomotive was not cut in for this event. Operations over a two-mile segment were used for simulating this event.

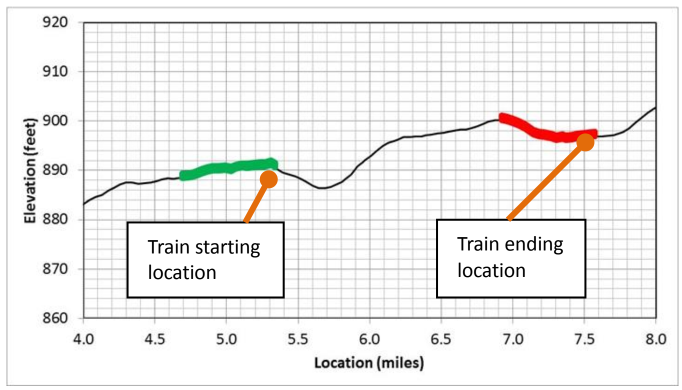

Figure 18. Track elevation profile for mixed train test.

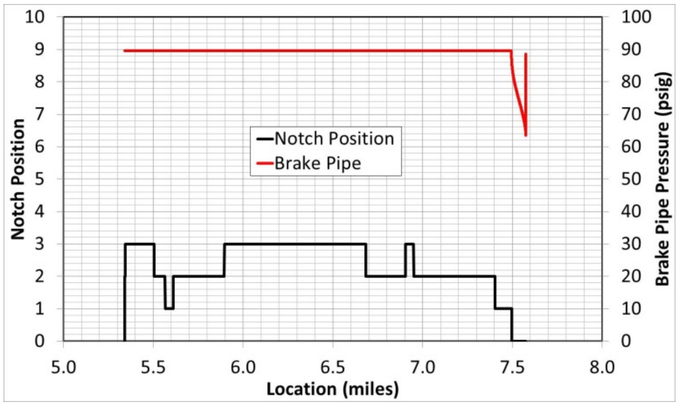

Figure 19. Train handling for mixed train startup and stop test.

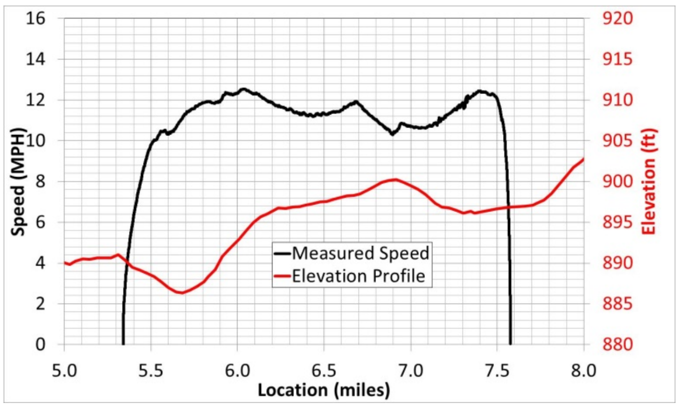

Figure 20. Measured speed profile for mixed train startup and stop test.

Figure 21 shows the comparison of the speed predicted by TEDS with the measured speed profile for this event. The maximum deviation is only about 0.5 MPH, which meets our criterion.

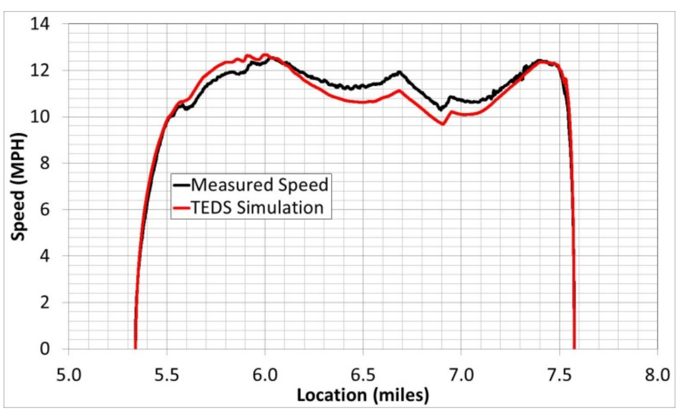

Figure 21. Comparison of measured and TEDS predicted speed Mixed Train - Startup and speed control event.

Figure 22 shows the comparison of the TEDS predicted coupler force with the measured coupler force on Test Car #3. All peaks are predicted, and the magnitude of the events meets our criterion for coupler force validation. The measured coupler force in train tests are noisy because the draft gear is a dry friction device. No data filtering was applied to the test data for plotting.

Figure 23 shows the comparison of the pressures predicted by TEDS on Test Car #3 with the measured data. The maximum deviation is within 5 psig, which meets our criterion.

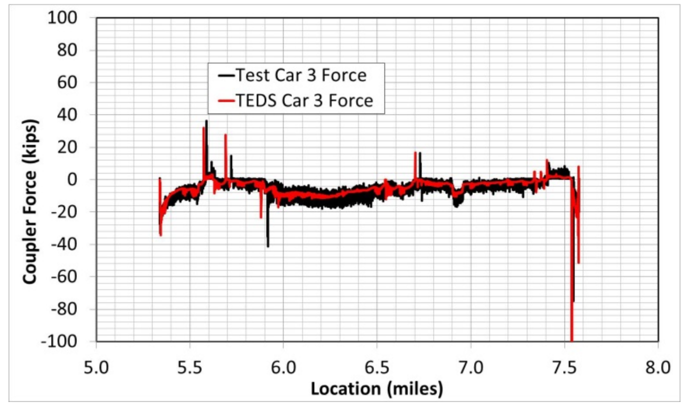

Figure 22. Comparison of TEDS predicted coupler force on Test Car #3 with measured coupler data.

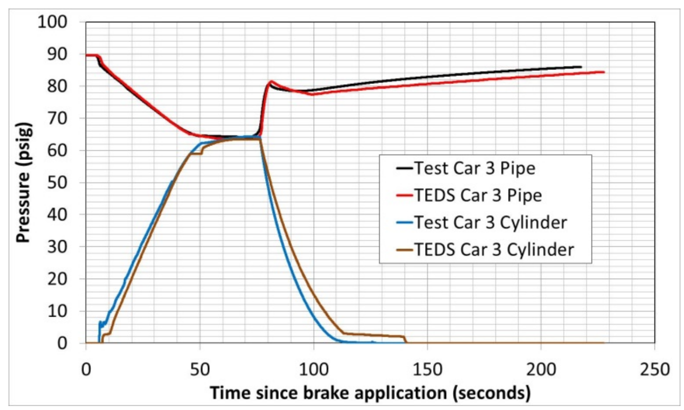

Figure 23. Comparison of TEDS predicted brake pipe and brake cylinder pressures on Test Car #3 with measured data.

CONCLUSIONS

Two revenue service train tests were conducted to obtain validation data for TEDS. The first was on a unit train, and the second was on a mixed manifest train operated with distributed power. Validation criteria were defined for the draft and brake systems and the train speed. For both trains several events were staged and data collected for comparison with TEDS predictions.

Train speed, brake pipe and brake cylinder pressure, and coupler force comparisons were made between the predictions of TEDS and the measured test data. All of the parameters matched closely with the test data, within the established validation criteria. The results of this revenue service validation testing and analysis further confirm the validity of TEDS to accurately simulate freight train operations.

ACKNOWLEDGMENTS

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The authors are grateful for the support of the late Mr. Kevin Kesler, Chief- Rolling Stock R&D Division.

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4 Manual of Standards and Recommended Practices, Association of American Railroads, Section E, 2013.

U.S. Department of Transportation
Federal Railroad Administration

OFFICE OF RESEARCH & DEVELOPMENT

Train Energy and Dynamics Simulator (TEDS) Simulation LNG Train (Tank Car DOT 113)

Project Update

693JJ618D000006

Task Order - 693JJ618F000138

May 15, 2020

SHARMA & ASSOCIATES, INC.

Overview

- Background
- Objective
- Routes details
- Train summary
- TEDS simulation on Route 1 & 2
- Safety analysis
  - Coupler forces
  - Wheel L/V ratio
- Operational speeds
- Comparison - Route 1 & 2
- Summary

Background

- FRA requested a train operation study using TEDS software for potential rail routes relevant to DOT-SP 20534, issued by PHMSA to Energy Transport Solutions, LLC (ETS).
- The special permit authorizes shipment of LNG by rail in 100-car unit trains between Wyalusing, PA and Gibbstown, NJ, on two routes each with length of approximately 411 and 355 miles, respectively, with no intermediate stops.

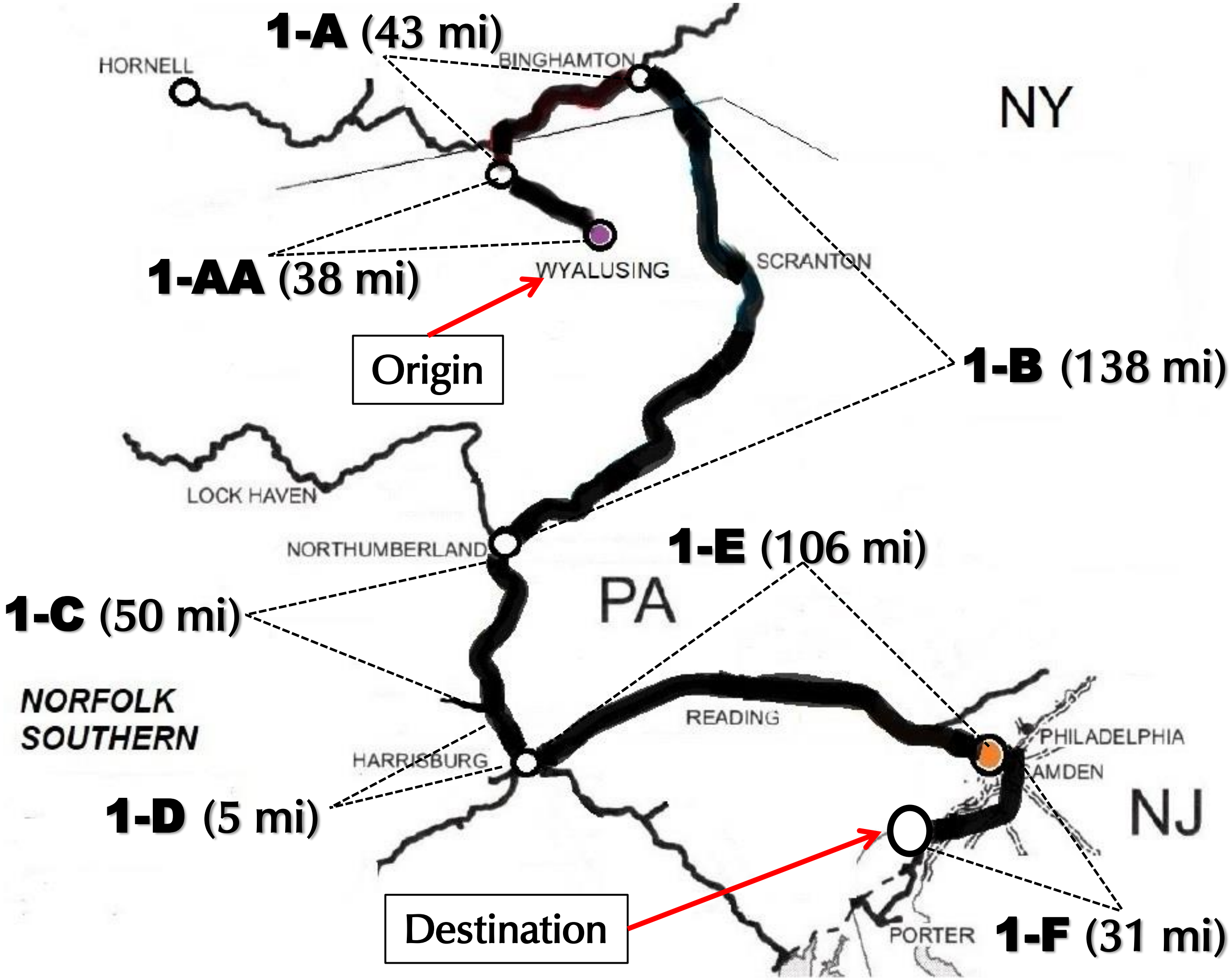
Objective

Conduct a safety assessment of the 100-car LNG train on two specified routes using TEDS simulation results for train handling, achieved train speed against the authorized speed limits, coupler forces and the wheel L/V ratio, i.e., a derailment tendency index.

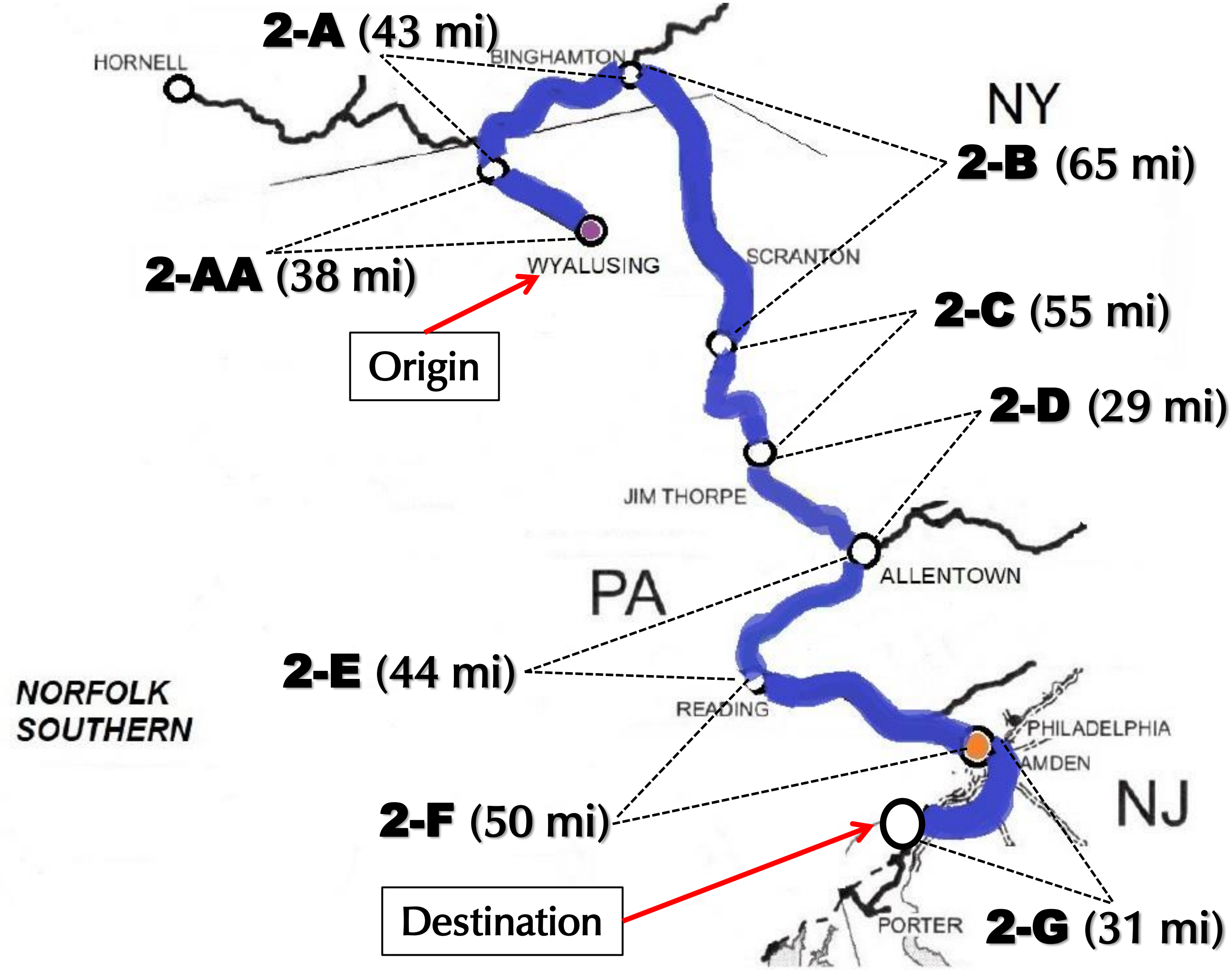
LNG Train Routes

Note: Significant overlap between the two Routes.

Details of Route 1 (~411 miles)



Details of Route 2 (~355 miles)



Details of LNG Routes

Route 1

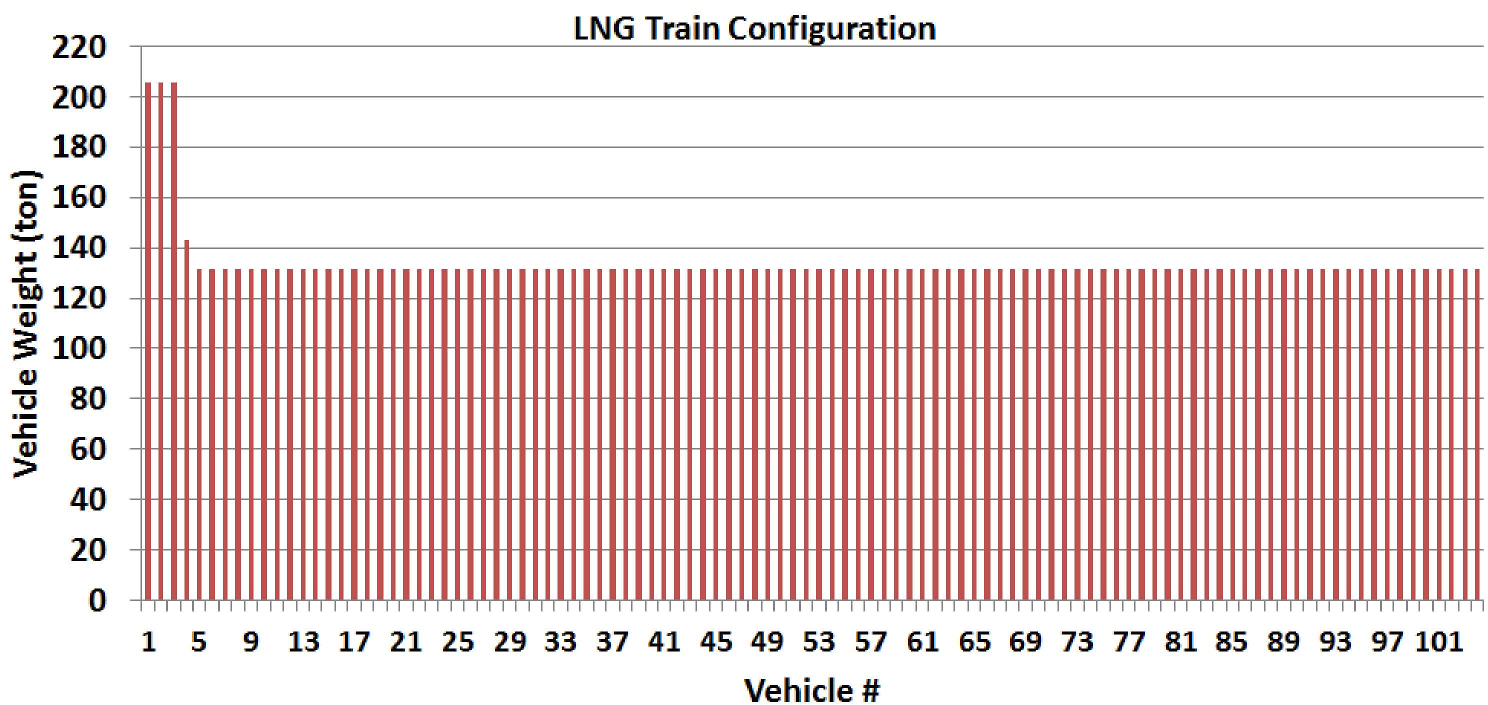
Leg	Start	End	Length (miles)
1-AA	Wyalusing	Waverly	38
1-A	Waverly	Binghamton	43
1-B	Binghamton	Northumberland	138
1-C	Northumberland	Enola	50
1-D	Enola	Harrisburg	5
1-E	Harrisburg	Philadelphia	106
1-F	Philadelphia	Gibbstown	31
Total			**411**

Route 2

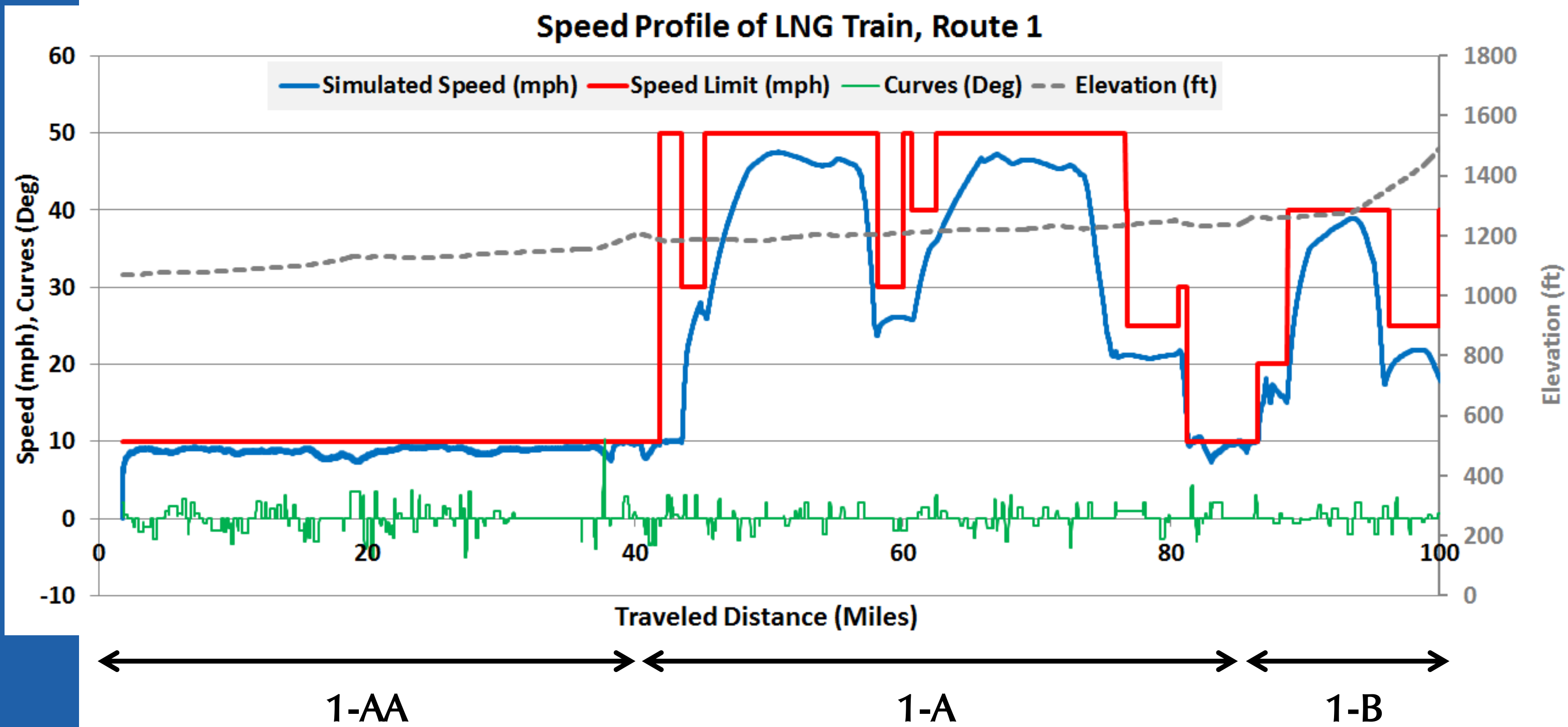
Leg	Start	End	Length (miles)
2-AA	Wyalusing	Waverly	38
2-A	Waverly	Binghamton	43
2-B	Binghamton	Dupont	65
2-C	Dupont	Jim Thorpe	55
2-D	Jim Thorpe	Allentown	29
2-E	Allentown	Reading	44
2-F	Reading	Philadelphia	50
2-G	Philadelphia	Gibbstown	31
Total			**355**

Train Configuration

- Head-end Power, Three (3) 4,400 HP AC Locos, 1 Buffer car and 100 DOT-113 tank cars
- Trailing Tonnage: 13,293 tons
- Total Train Length: 8,462 ft HP/ton: 0.9



Speed Profile of LNG Train - Route 1



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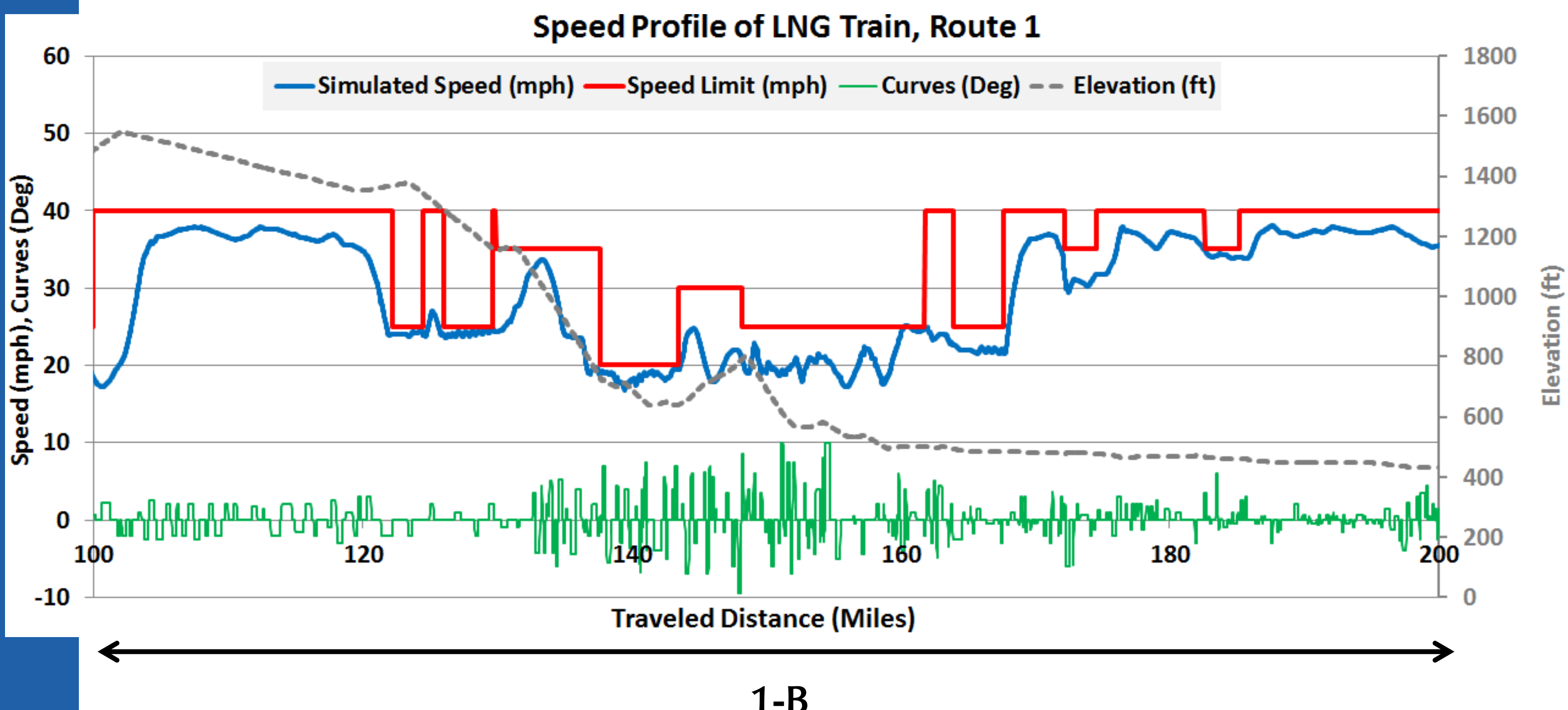
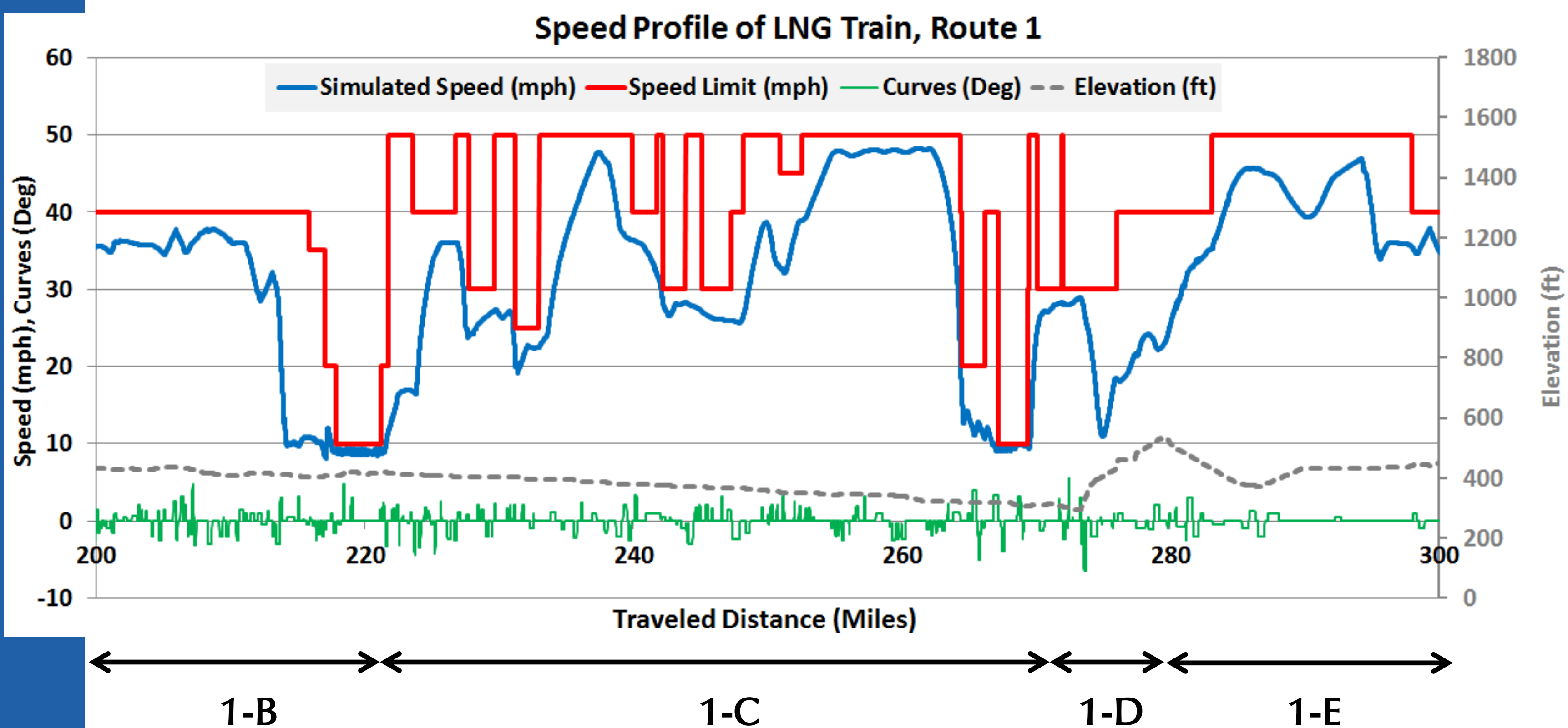
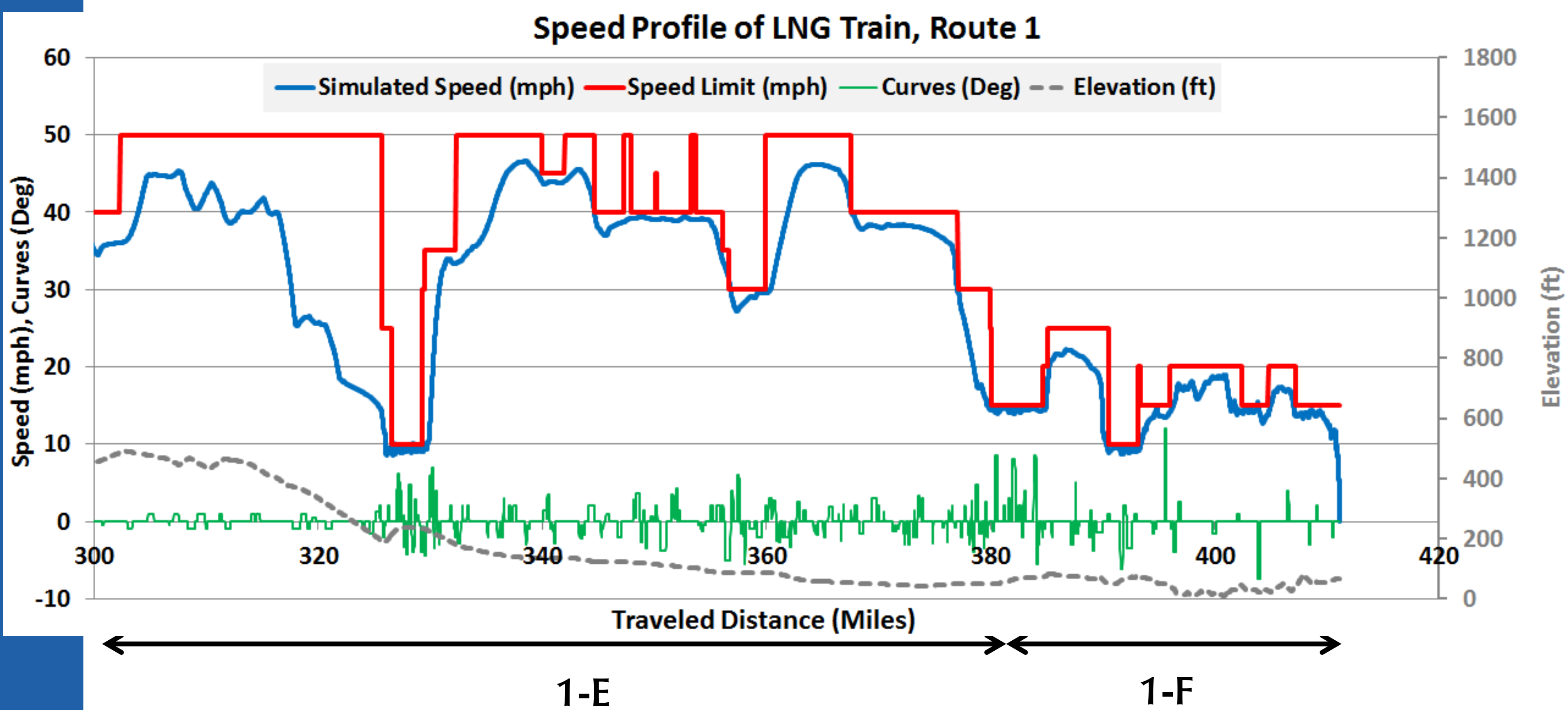
Speed Profile of LNG Train - Route 1..



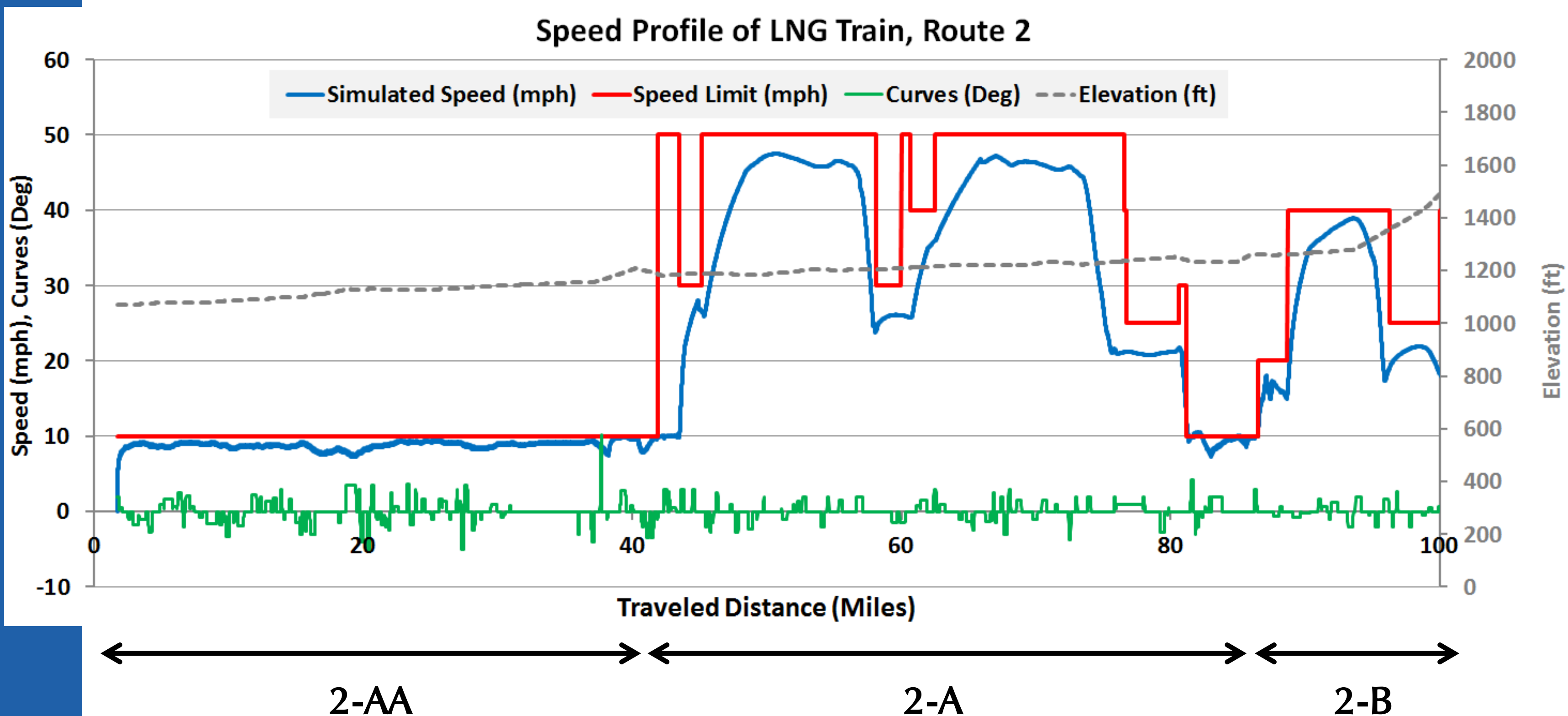
Speed Profile of LNG Train - Route 1..



Speed Profile of LNG Train - Route 1..



Speed Profile of LNG Train - Route 2



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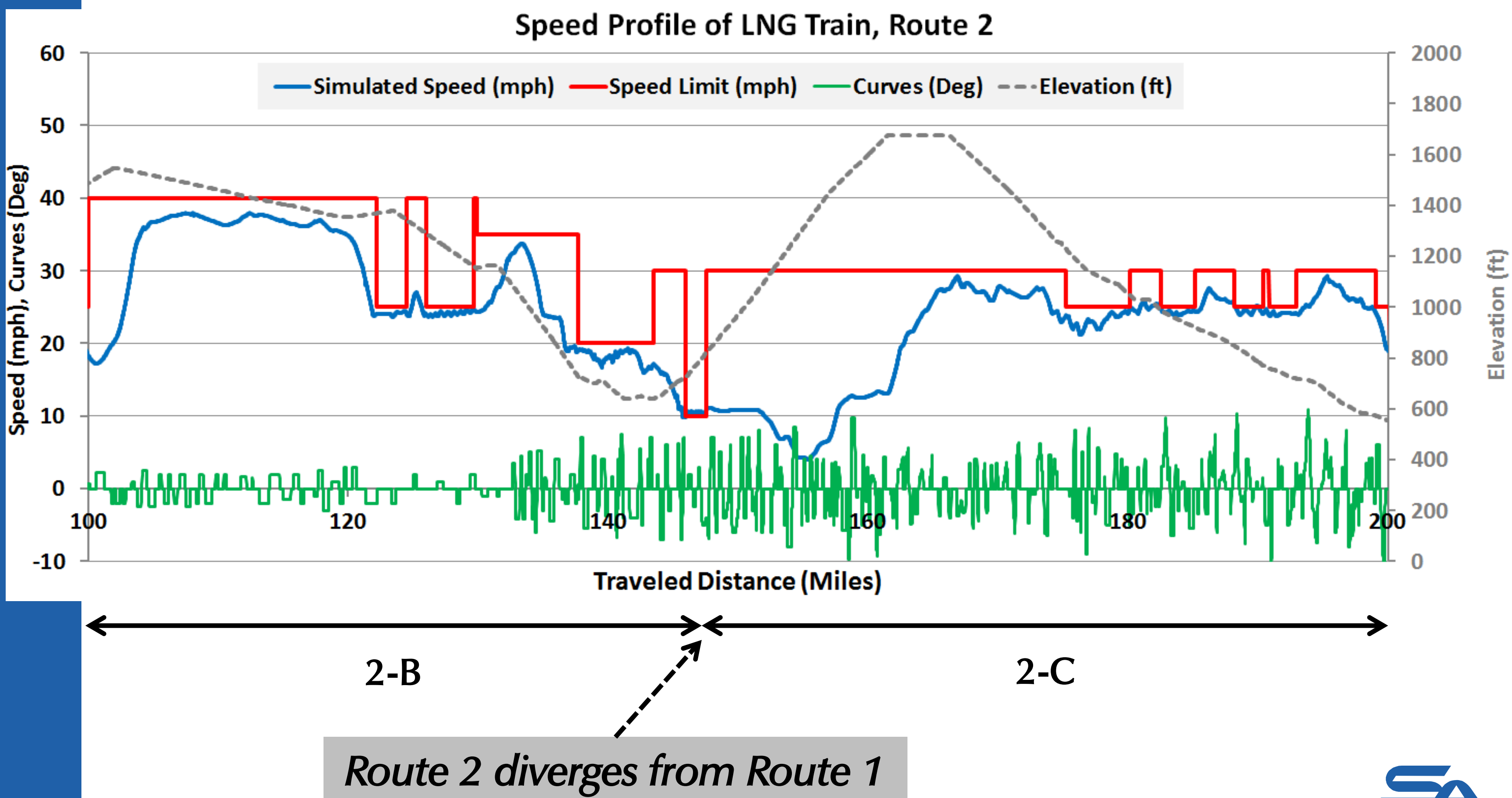
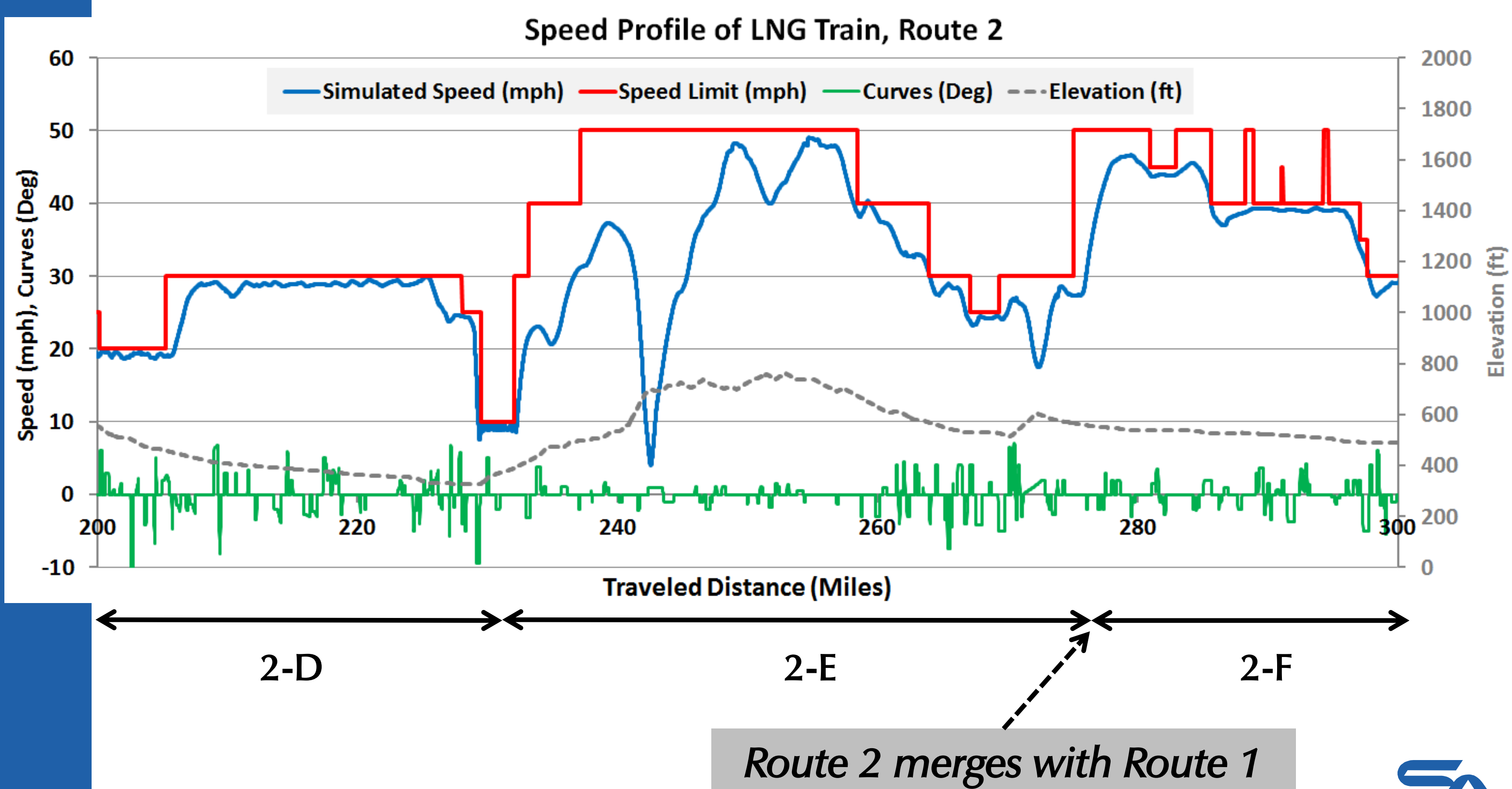
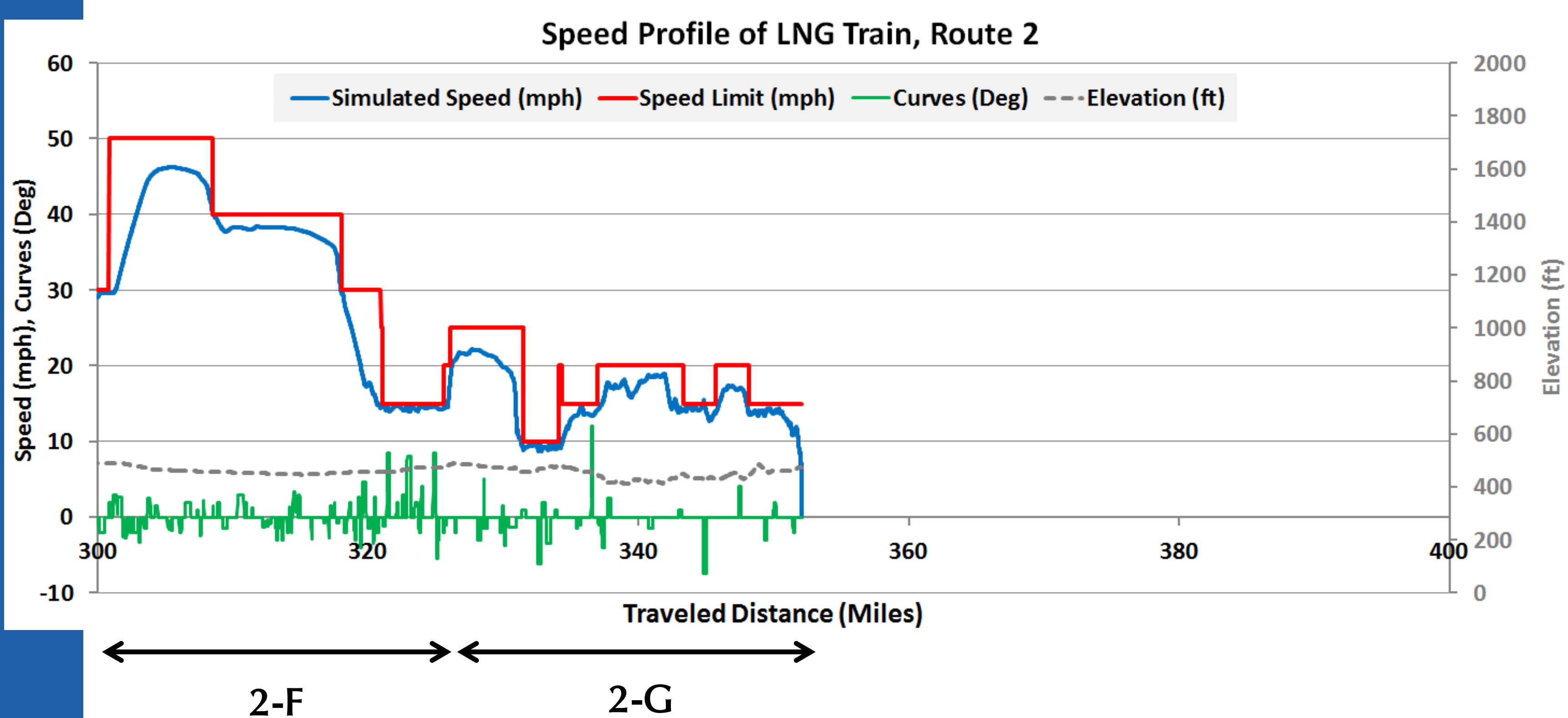


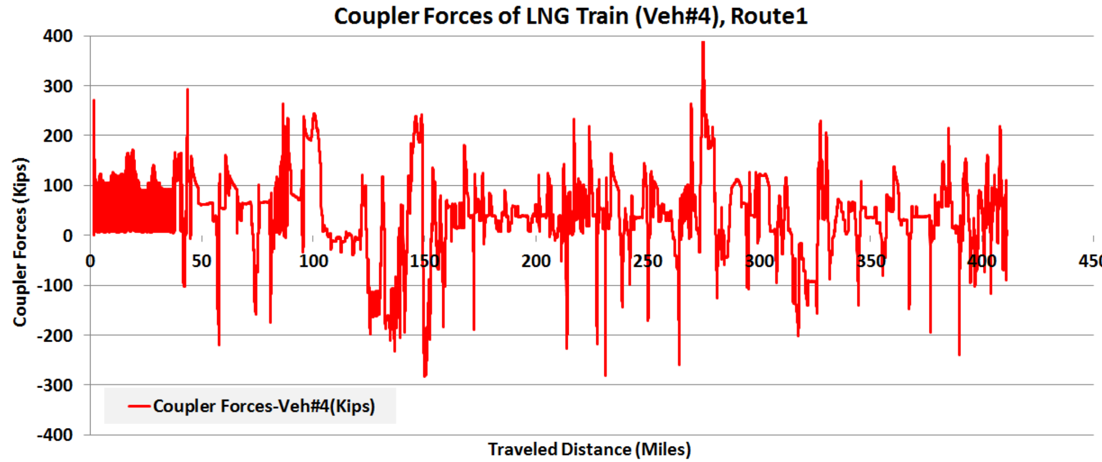
Speed Profile of LNG Train - Route 2..

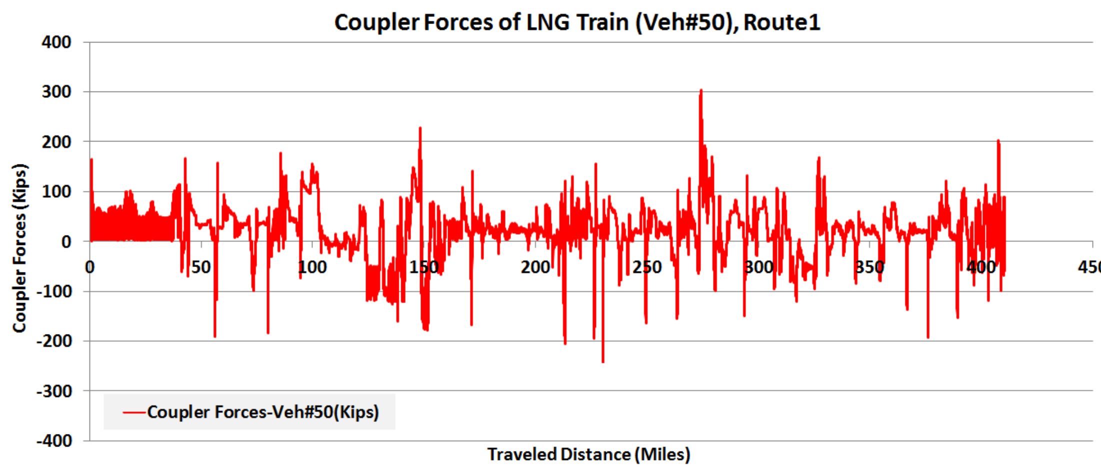


Speed Profile of LNG Train - Route 2..



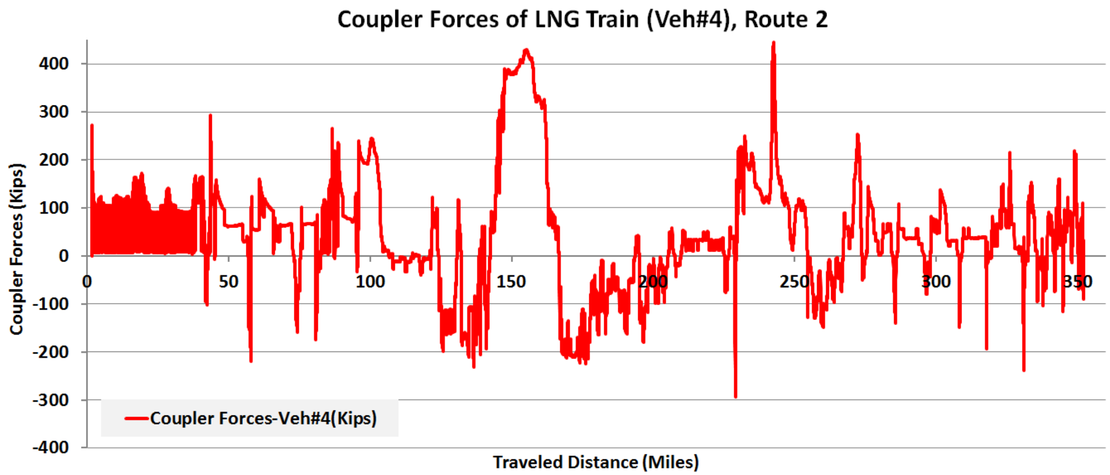
Coupler Force (Front end) Vehicles #4 & #50 (Route 1)

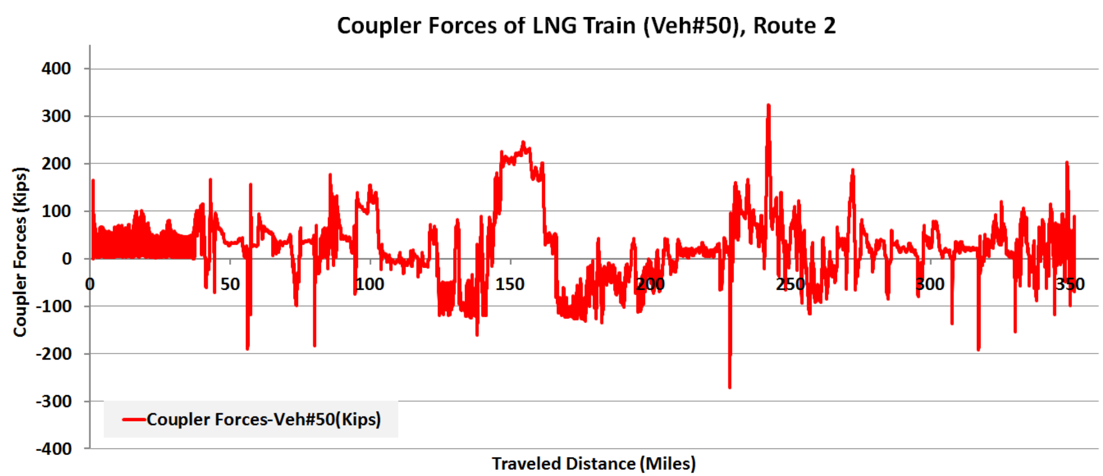




Note: Generally, forces in the front half of train are higher. Transient peak coupler forces are expected under significant grade and throttle/DB changes. High buff forces in curved territories may increase derailment risk.

Coupler Force (Front end) Vehicles #4 & #50 (Route 2)

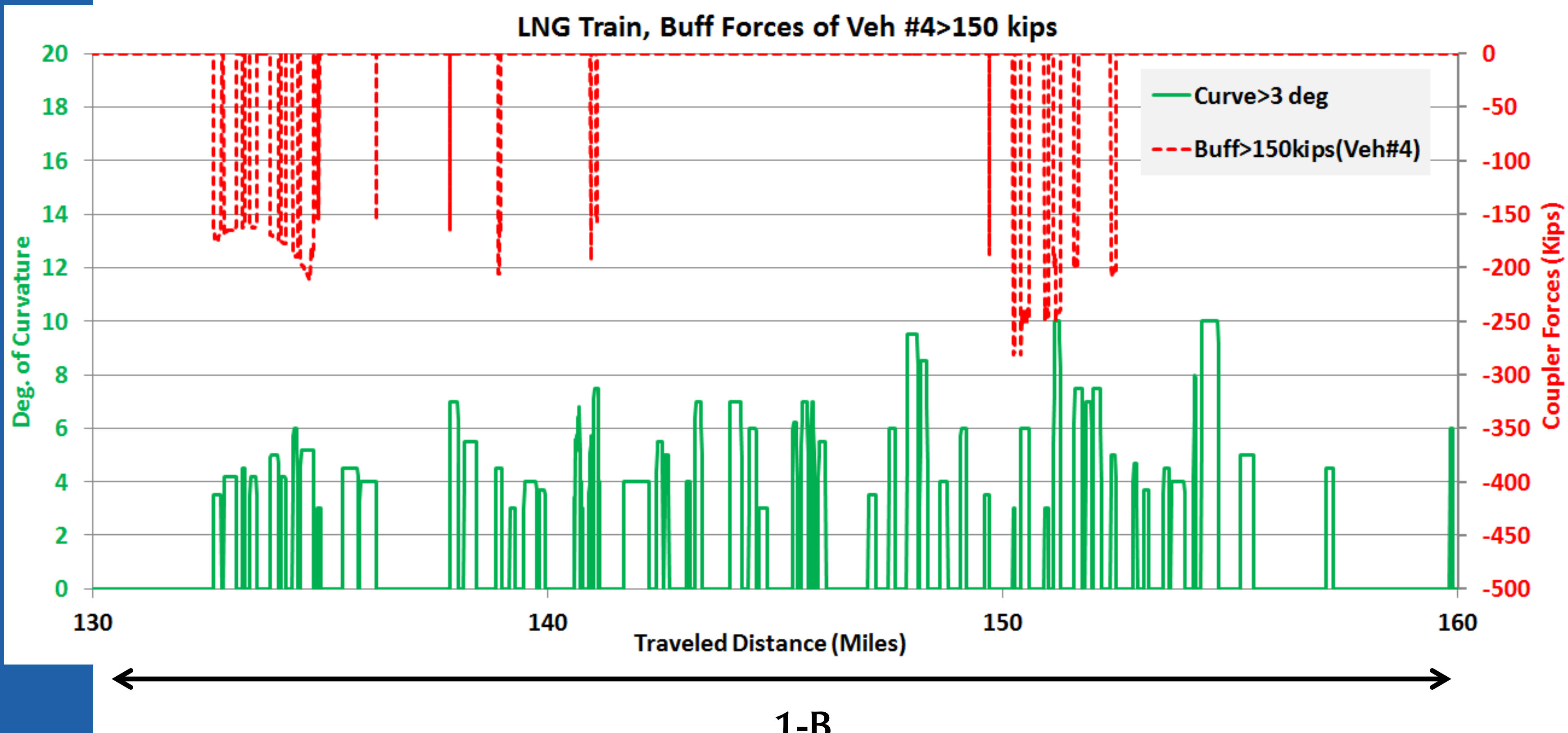




Note: Generally, forces in the front half of train are higher. Transient peak coupler forces are expected under significant grade and throttle/DB changes. High buff forces in curved territories may increase derailment risk.

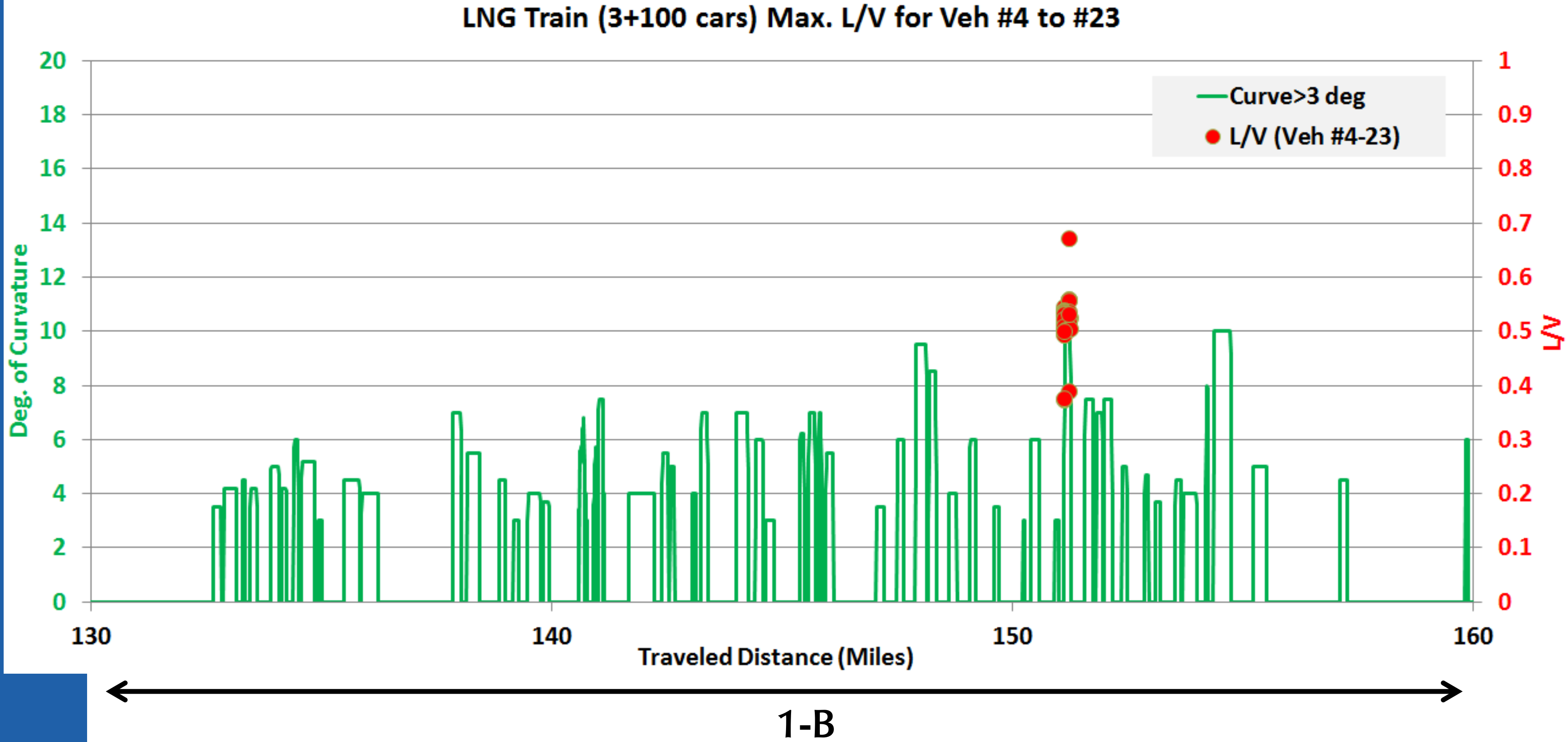
TEDS Simulation – LNG Train (DOT113)

Coupler Force (Buff) on Vehicle 4, in Curves>3 deg. (Route 1)



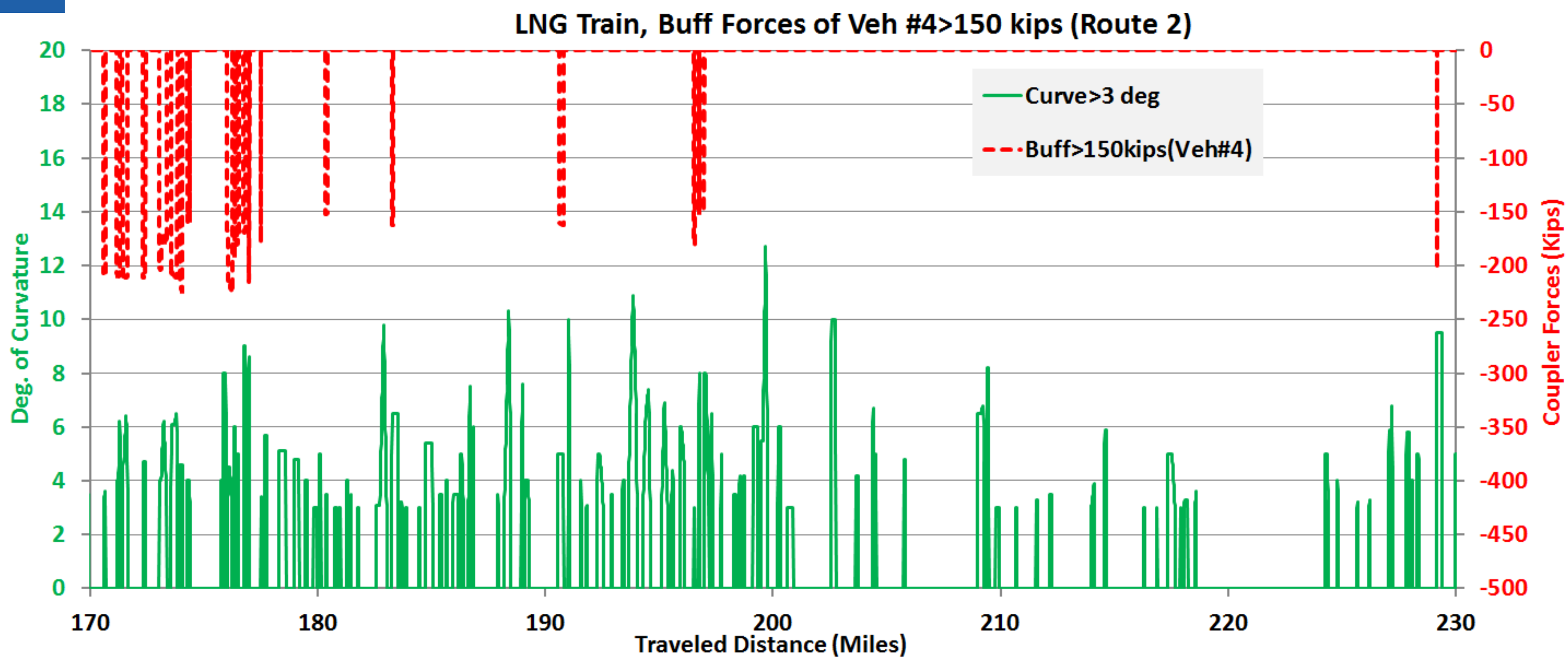
Note: Curves are shown with magnitude of degree of curvatures. Buff force can be more safety critical during negotiation.

Predicted Max L/V for Selected Vehicles (#4-23) through Critical Part of Route 1



Note: Curves are shown with magnitude of degree of curvatures.
An L/V ratio of >0.8 is considered a derailment risk.

Coupler Force (Buff) on Vehicle 4, in Curves>3 deg. (Route 2)

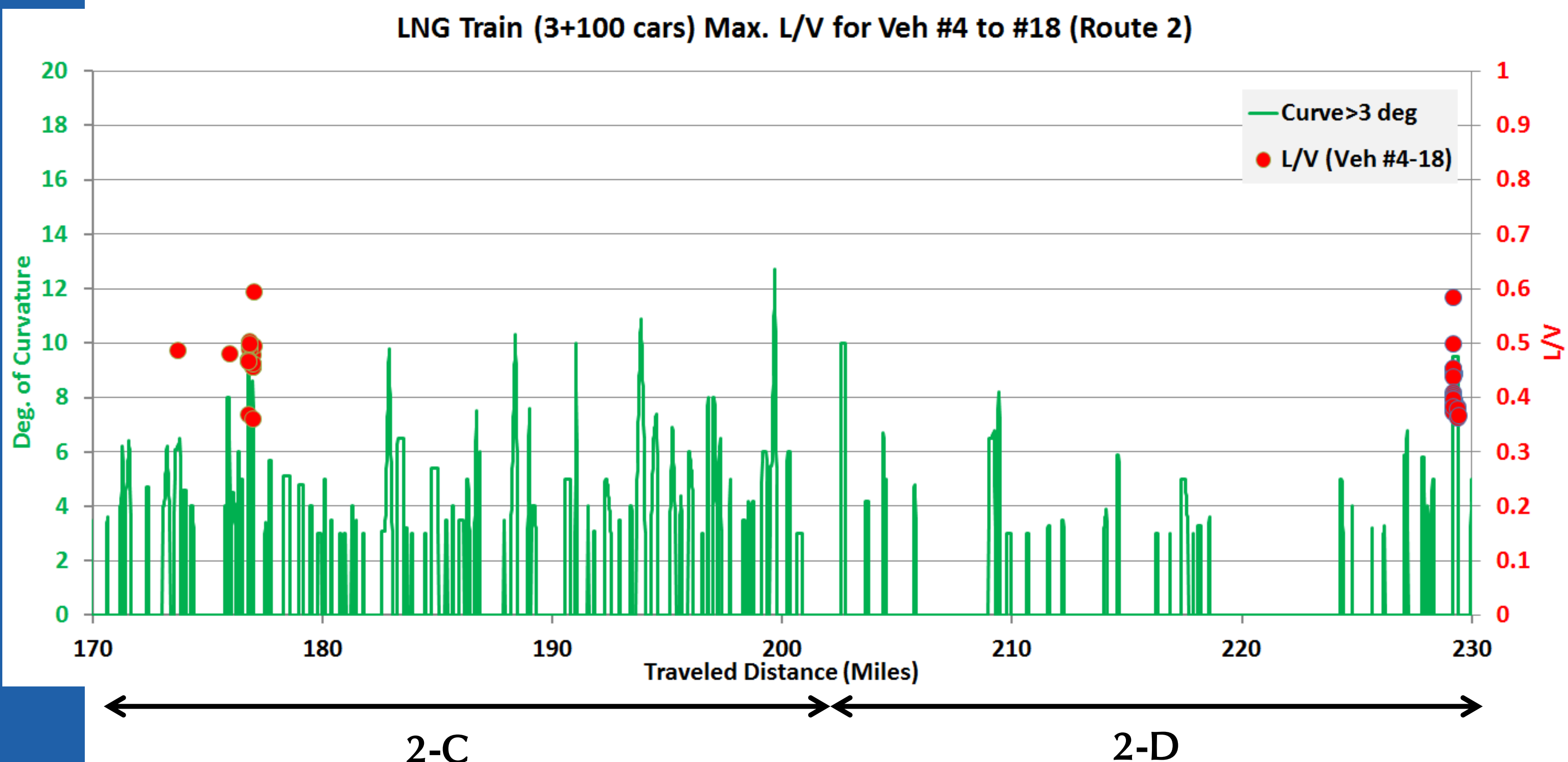


2-C

2-D

Note: Curves are shown with magnitude of degree of curvatures.
Buff force can be more safety critical during negotiation.

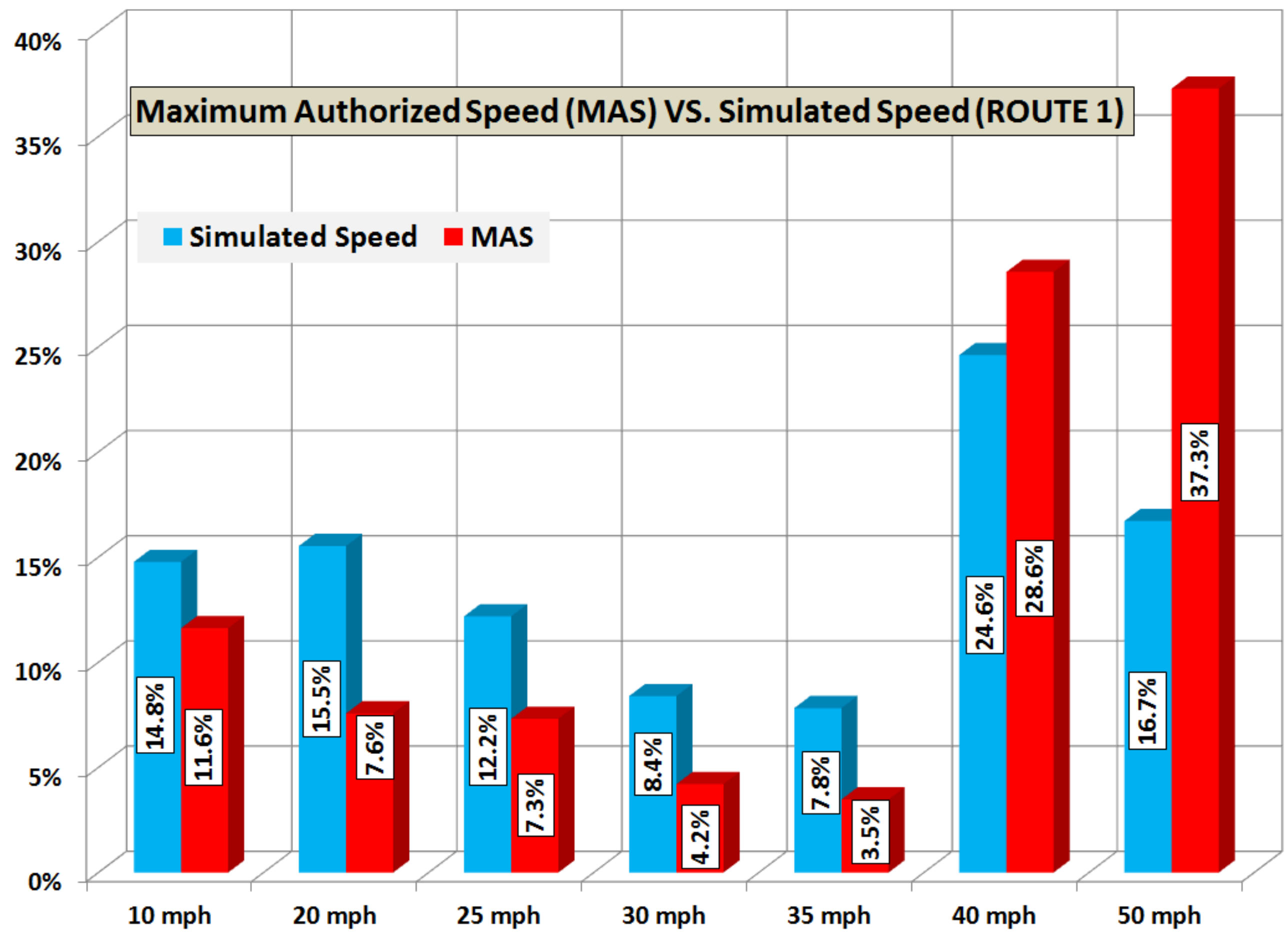
Predicted Max L/V for Selected Vehicles (#4-18) through Critical Part of Route 2



Note: Curves are shown with magnitude of degree of curvatures.
An L/V ratio of >0.8 is considered a derailment risk.

Comparison-Speed Distribution (Route 1)

MAS (Timetable Data) VS. Simulated Predicted Speed

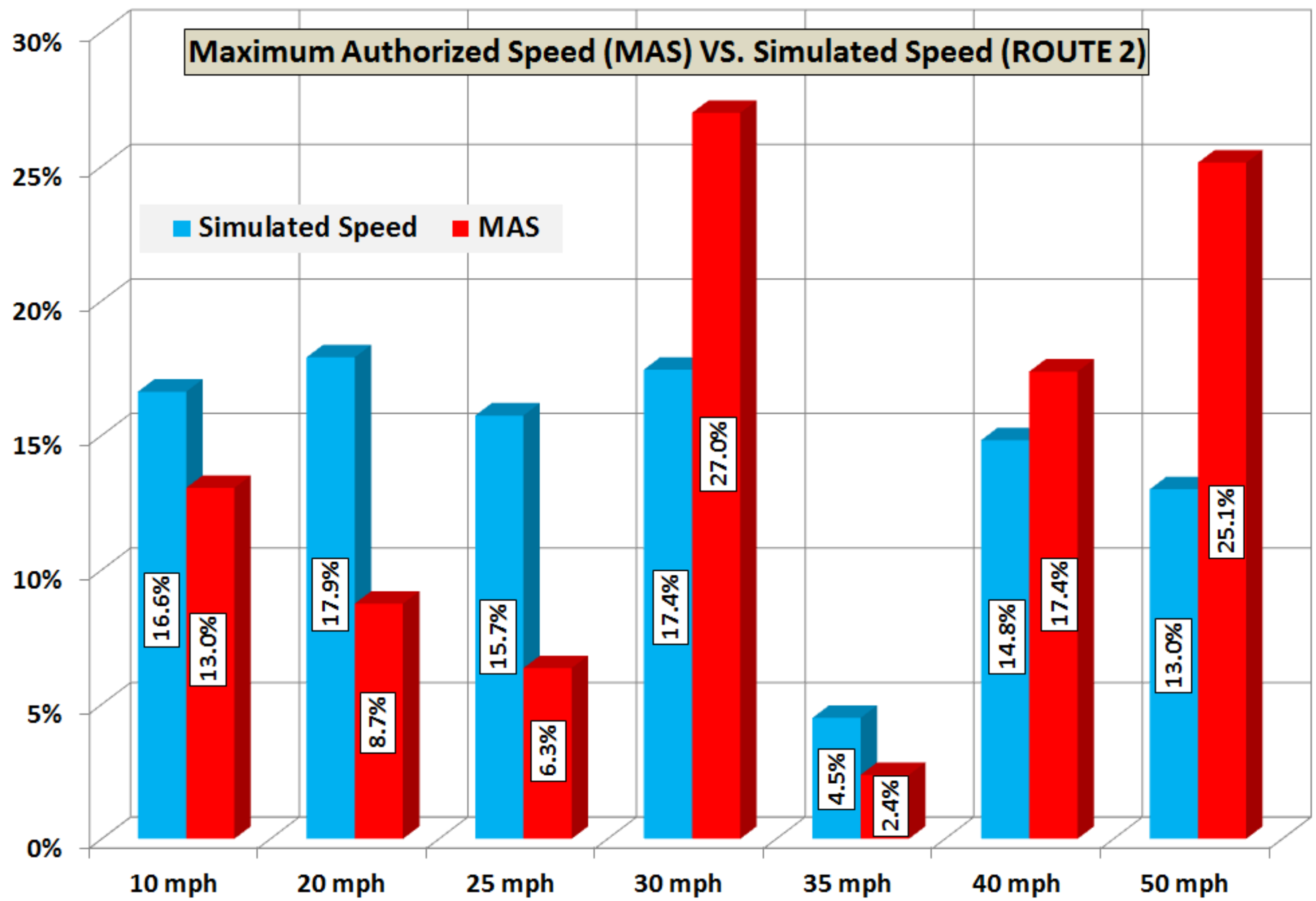


Note: Only 11.6% of Route has 10 mph speed limit, but train runs at 10 mph over 14.8% of the route.

TEDS Simulation – LNG Train (DOT113)

Comparison-Speed Distribution (Route 2)

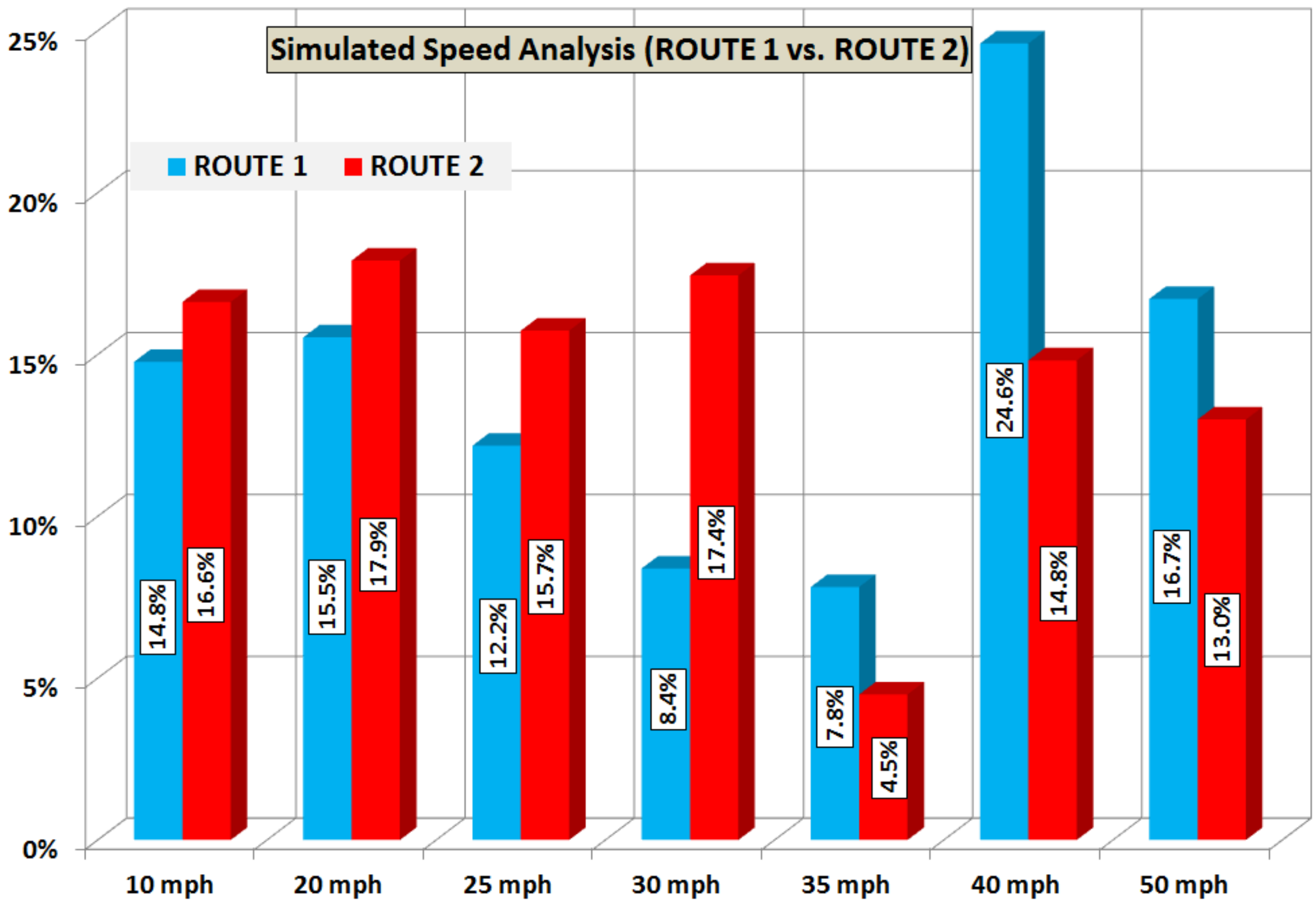
MAS (Timetable Data) VS. Simulated Predicted Speed



Note: Only 13% of Route has 10 mph speed limit, but train runs at 10 mph over 16.6% of the route.

Simulated Speed Comparison

(Route 1 vs. Route 2)



Comparison - Route 1 vs. Route 2

Parameter	Route 1	Route 2
Length (miles)	411	355
Travel time (hours)	19.6	18.8
Avg. Operational speed (mph)	20.9 *	18.8 **
Avg. MAS (mph)	37.0	33.1

** Simulated Route 1 distance: 410 miles, TEDS simulated train operation time: 19.6 hours.*
*** Simulated Route 2 distance: 354 miles, TEDS simulated train operation time: 18.8 hours.*

Route 1 average speed is 20.9 mph, i.e., 2.1 mph higher than Route 2 speed of 18.8 mph.

Analysis Summary

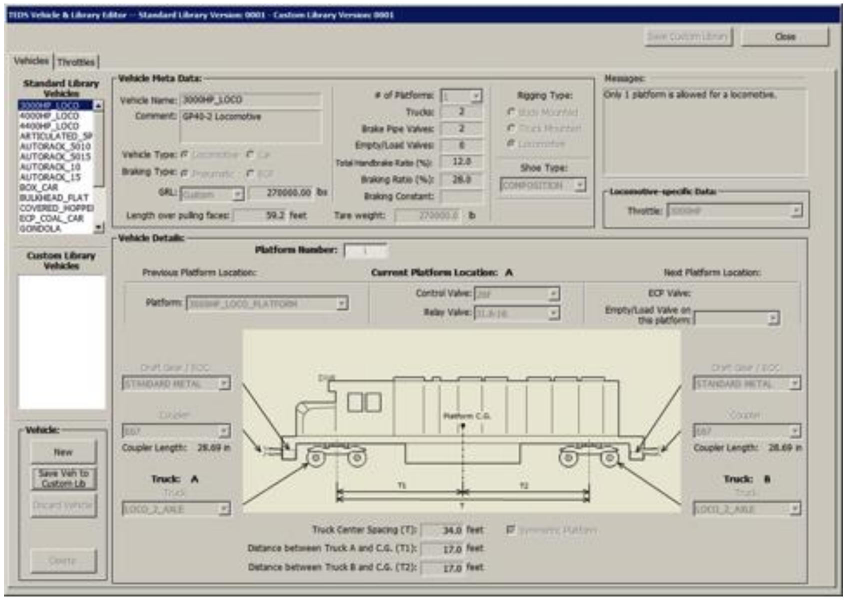
- TEDS train handling of the LNG train to meet speed limits given the grade and curves characteristics is reasonable for both routes.
- Simulation results and the analysis show that the coupler forces and the L/V values are reasonable and within the industry practice safety limits and indicate no obvious cause for concerns.
- Route 1 characteristics, i.e. grades and curves are less severe than Route 2, resulting in speed 20.9 mph, i.e., 2.1 mph higher than Route 2.

TRAIN ENERGY AND DYNAMICS SIMULATOR (TEDS)

With the Federal Railroad Administration (FRA)'s support, Sharma & Associates, Inc. (SA) is pleased to offer a state-of-the-art train dynamics evaluation tool, TEDS, for use by the railroad industry and academia. TEDS (Train Energy and Dynamics Simulator) is a software tool designed and developed for studying and simulating train safety and performance. Version 2.0 of the program is now available, and may be used for modeling train performance under a wide variety of equipment, track, and operating configurations.

TEDS Capabilities:

- Modern AC & DC traction locomotives
- A wide variety of freight cars
- Head end power and distributed/remote power
- Current brake systems, including Electronically Controlled Pneumatic (ECP) brakes
- Modern coupling systems including M-901G draft gears and end-of-car cushioning units with or without preload
- All locomotive/train control operations available to locomotive engineers
- User interface to prepare input data, run simulations, and post-process results



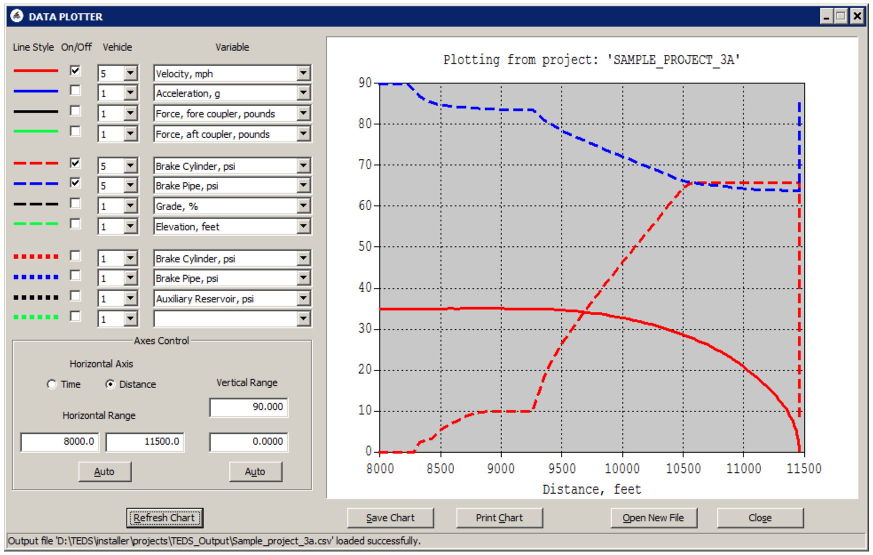
Potential Applications:

- Conducting safety and risk evaluations related to train handling, train makeup or operations
- Incident/accident/derailment investigations
- Energy consumption studies
- Motive power performance & optimization
- Ride quality evaluations
- Brake system performance & stopping distance evaluations

TEDS has been validated using available published data and a validation report has been published. Additional validation effort is also underway.

SHARMA & ASSOCIATES, INC.

Technical Basis:



- Simulates operation of a defined train over defined track with defined handling.
- A PC based program with a user friendly, Graphical User Interface (GUI) for input of train, track, and handling, and graphical review of simulation output.
- Solves differential equations of motion to calculate the dynamics of each vehicle, incorporating appropriate forces and resistances.
- Each locomotive and car is modeled as a lumped mass to calculate intercar run-in and run-out forces.
- High-fidelity fluid mechanics model of braking system is built-in.
- Extensive library of cars and components for building trains with ability to add custom cars and components.

SA will offer online access to TEDS through:

- Exclusive, secure, remote access to server located at Sharma & Associates to run TEDS
- User manual
- Training in use of TEDS, either via webinar or at Sharma & Associates Countryside offices; on-site training can be arranged with additional charges
- Initial Library of cars and locomotives for building trains
- Technical support

Other Support:

- When requested, SA will enter into a Non-Disclosure Agreement with the Licensee to provide additional safeguards.
- Periodic maintenance and bug fixes will be provided, as available.
- Requests for specific enhancements will be considered and incorporated into the software, as appropriate.
- SA will arrange for user meets/conferences with a frequency that is based on user interest.
- A regular newsletter will be published, with updates, 'tips & tricks', and case studies.

For Additional Information, Please Contact:

Sharma & Associates, Inc.
100 W. Plainfield Rd.
Countryside, IL 60525

(708)-588-9871
TEDS-Request@sharma-associates.com

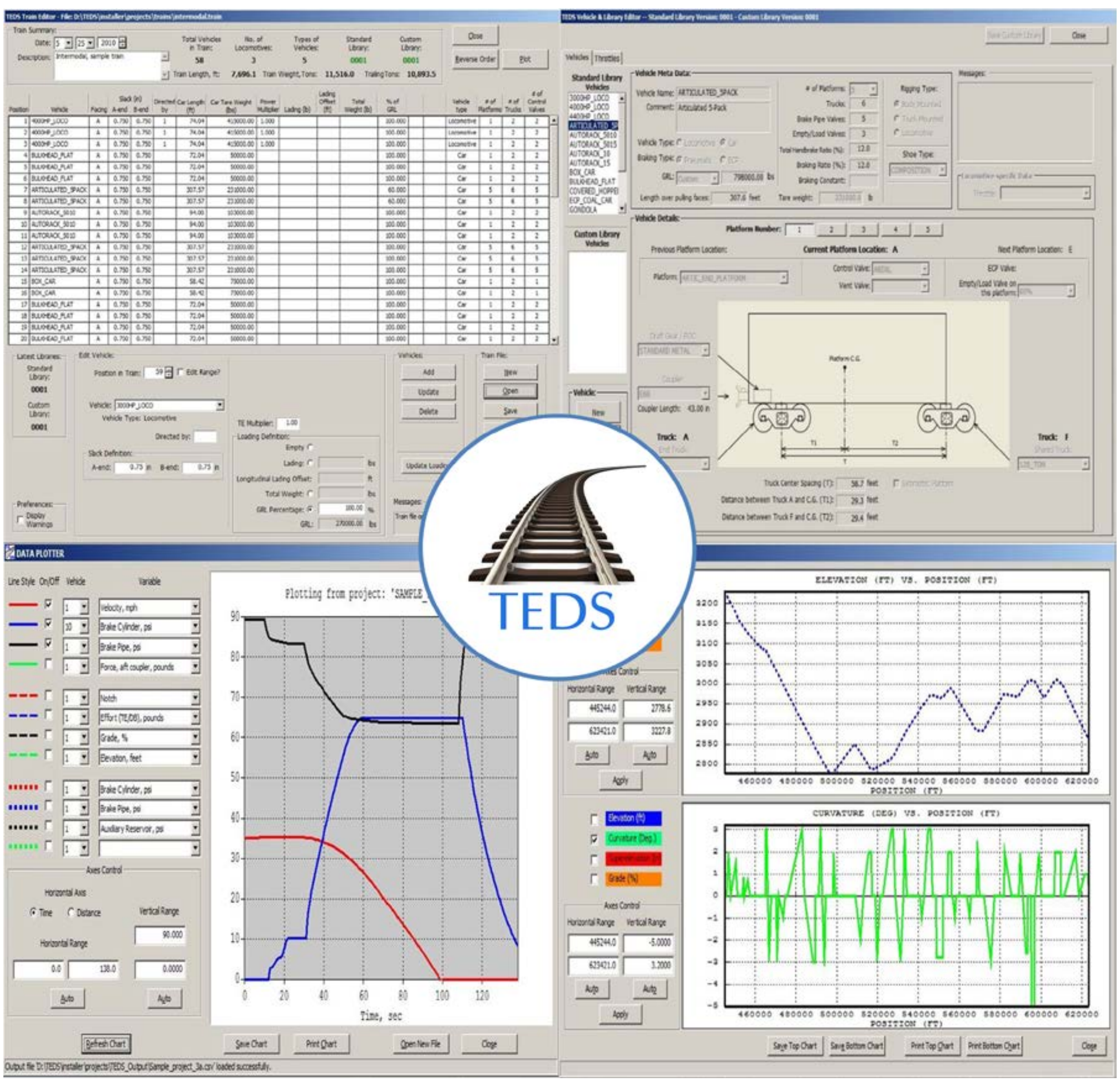
SHARMA & ASSOCIATES, INC.

U.S. Department of
Transportation

Federal Railroad Administration

VALIDATION OF THE TRAIN ENERGY AND DYNAMICS SIMULATOR (TEDS)

Office of Railroad
Policy and Development
Washington, DC 20590



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January 2015

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13. ABSTRACT (Maximum 200 words)

FRA has developed Train Energy and Dynamics Simulator (TEDS) based upon a longitudinal train dynamics and operations simulation model which allows users to conduct safety and risk evaluations, incident investigations, studies of train operations, ride quality evaluations, and evaluations of current equipment and new equipment designs.

This document describes how TEDS modelling software predictions were validated with publicly available data in order to establish a sufficiently high level of confidence for users, which will enable them to conduct studies and investigations with TEDS. This report describes the approach to validating TEDS and the associated criteria that were adopted for this purpose, and it discusses validating the model at the train level as well as validating simulations of the braking systems (both pneumatic and electronically controlled pneumatic (ECP)) and the coupling systems (both draft gears and cushioning units). Train level validation was accomplished using available velocity profiles, coupler forces, brake pipe and brake cylinder pressures and stopping distance data from for well documented published and publicly available sources.

After the validation process concluded, it was evident that TEDS is a high fidelity model that realistically predicts longitudinal train behavior under a variety of operating conditions, including acceleration, braking, steady state running, hilly terrain operation, and certain emergency conditions. Further, it demonstrated that TEDS' predictions are realistic for both gross train dynamics, which is measured by parameters such as position, velocity, and stopping distance, as well as inter-car dynamics, which is measured by parameters such as coupler forces.

14. SUBJECT TERMS

Air brake, Coupler forces, Draft gear, Dynamic braking, ECP braking, End of car cushioning, Slack action, Stopping distance, Tractive effort, Train dynamics validation, Train operation

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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

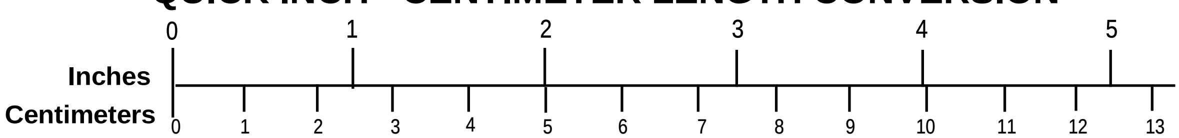
VOLUME (APPROXIMATE)

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°

Contents

Illustrations

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Executive Summary

To support the development and evaluation of existing and proposed safety regulations and guidelines, improve railroad operational safety, and conduct analyses and investigations of railroad incidents, the Federal Railroad Administration (FRA) funded the development of a longitudinal train dynamics simulator named the Train Energy and Dynamics Simulator (TEDS). This validation report demonstrates that TEDS is a high fidelity model that realistically predicts longitudinal train and component behavior under a variety of operating conditions, including acceleration, braking, steady state running, over hilly terrain, and certain emergency conditions.

TEDS has the capability to conduct safety and risk evaluations, incident investigations, train operation and energy consumption studies, ride quality evaluations, and evaluations of current equipment and new equipment design. It takes user-specified details about train consist, track characteristics and train handling in order to simulate the longitudinal dynamics and energy consumption resulting from the operation of a train over a section of track.

Because intended users are going to apply this simulation to a wide range of uses, they need to be confident that TEDS delivers reliable results. This confidence is typically established through model validation.

In this document, the validation process is described at both the component and system level. Coupler forces and air brake system response are validated at the component level using a variety of publicly available source data.

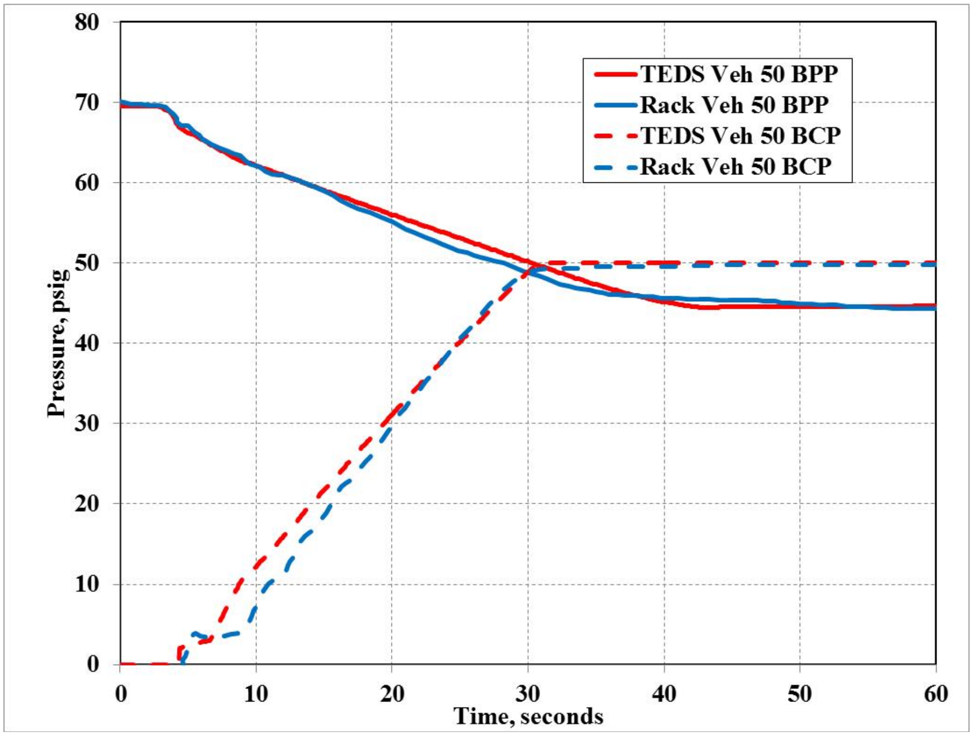
Air brake model predictions are verified by comparing TEDS simulations of braking behavior to data from published sources including air brake test rack data from the the American Society of Mechanical Engineers (ASME) and Air Brake Association proceedings (referenced in the report), specifications from the Association of American Railroads (AAR) Standards and Recommended Practices, and descriptions from air brake manufacturers' instructional brochures. During the development phase, the published and collected data were used to check the model's formulation and the integrity of results it yielded. These comparisons show that TEDS accurately represents both conventional pneumatic and electronically controlled pneumatic (ECP) brake system characteristics, such as brake cylinder pressure build-up and release rates, supply reservoir and brake pipe response.

For system level validation, several train accidents investigated by the National Transportation Safety Board (NTSB) were used to compare train behavior before the accidents. These allowed establishing the predictive capability of TEDS over significantly long track segments. Additional system level validation was supplied by a complete set of train test data from the AAR publication R-799. This volume was prepared in the early 1990s by the AAR to serve as a validation document for those using the Train Operation and Energy Simulator (TOES), which is the AAR's own proprietary longitudinal train dynamics and operation simulation model. This report contains test data collected from a revenue service unit coal train.

When TEDS-predicted forces were compared with this measured data, the predictions were reasonable and well within the validation criteria; i.e. they capture the event, its trends, and predict a magnitude of the associated variable in reasonable agreement with the measured test

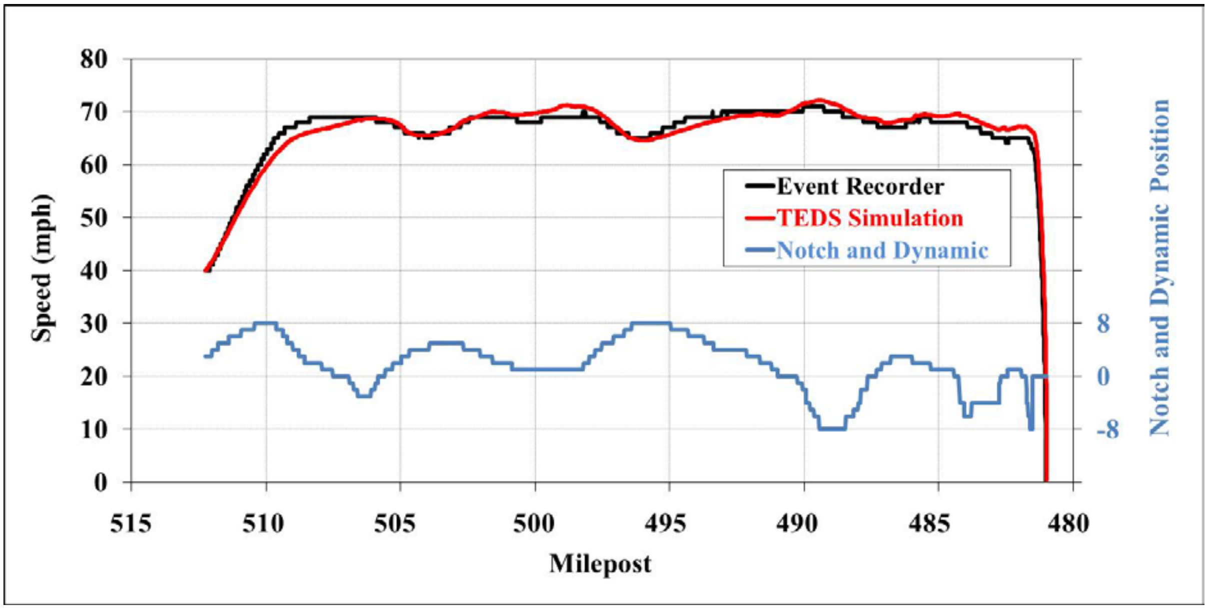
data. Similarly, TEDS predictions of train speed and air brake system pressures correlate closely with the measured data as shown in the following charts.

The chart below shows a sample comparison of TEDS air brake system predictions with test rack data for a full service application on a 50 car train. The brake pipe and brake cylinder pressures predicted by TEDS match the measured data very well.



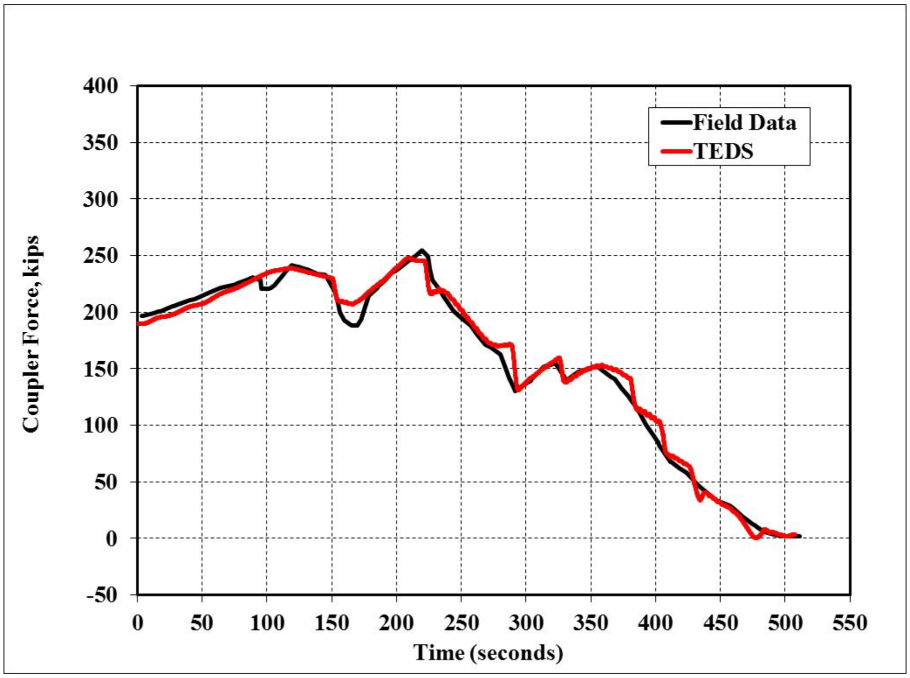
Comparison of test rack data and TEDS simulation for full service application, vehicle 50

The second chart shows the train speed predicted by TEDS compared to event recorder data for approximately 30 miles of simulation. The predictions closely match the event recorder speed.



Westbound Goodwell, OK train handling and speed comparison

The third chart shows the coupler force predicted by TEDS compared to measured test data for a cresting event on a unit coal train. The coupler force predicted by TEDS matches the measured test data very well.



Comparison of predicted to measured coupler force on selected car for the cresting operation

1. Introduction

To support development and evaluation of safety regulations and guidelines, develop and assess proposed standards to improve railroad operational safety, and conduct analyses and investigations of railroad incidents, the Federal Railroad Administration (FRA) funded the development of Train Energy and Dynamics Simulator (TEDS) software to perform longitudinal train dynamics simulations. After users specify the train consist, track characteristics, and train handling data, TEDS simulates the longitudinal train dynamics and energy consumption resulting from the operation of a train over a section of track.

These simulations offer invaluable opportunities for conducting safety and risk evaluations, incident investigations, studies of energy consumption and train operations, ride quality evaluations, and evaluations of both new and current equipment. They also have wide range of potential uses for the following:

- Evaluating the effectiveness of operating rules (current and proposed)
- National Transportation Safety Board (NTSB) accident investigations and evaluations of potential impact of proposed rules
- Examining the impact of speed limits on rail line capacity
- Evaluating of mixed equipment consists and related operating practices on safety and efficiency
- Studying the effect of new equipment design on train operation
- Train handling parametric studies
- Developing Positive Train Control (PTC) braking routines for speed and stop enforcement algorithms
- Optimizing motive power trains and routes
- Safety evaluations for electronically controlled pneumatic (ECP) braking

TEDS is a complex and comprehensive simulation tool that can be used to study how train dynamics is affected by the type of equipment in the train, the track profile, train handling, train make-up, etc. The usefulness of TEDS is highly dependent on its ability to produce simulation results that are realistic and reasonable so they can be used to draw conclusions and make decisions. To develop a level of confidence in the predictions produced by any simulation model, validating the model is generally required. If a model is validated, it can be used to conduct studies and investigations with a certain level of confidence in the results obtained.

This report discusses TEDS validation by splitting the process into two major areas:

- *Component-level validation*: The air brake system and the coupling force system were separately validated to ensure that these elements predicted behavior that was consistent with the expected behavior. The results of simulated air brake system performance were compared with measured data from an air brake test rack and results of simulations of ramp impact coupler forces with measured data.
- *System-level validation*: After the individual components were validated, simulations of the air brake system (brake pipe propagation, brake cylinder pressure for application and release) predictions of train speed, stopping distance, and coupler forces in the train were compared with previously measured train performances.

Overall, the validation process demonstrated that TEDS is a high fidelity model that realistically predicts longitudinal train behavior under a variety of operating conditions, including acceleration, braking, steady state running, hilly terrain operation, and emergency conditions. Further, this process revealed that TEDS' predictions are realistic for both gross train dynamics, which is measured by parameters such as position, velocity, and stopping distance, as well as inter-car dynamics, which is measured by parameters such as coupler forces.

2. Approach to Validation

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

a. Validation 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.

b. 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.

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

The following three criteria were used to validate TEDS:

1. TEDS should predict the occurrence of an event that was observed in the test.
2. TEDS should predict the trend of each parameter (coupler force, brake pipe and brake cylinder pressure, vehicle speed, etc.) that was involved in the event.
3. TEDS should be able to predict the amplitude of the parameter of the event reasonably well. What constitutes "reasonably well" is discussed below in a context specific to the parameters of interest.

For validation of coupler force predictions, a peak coupler force value within ±20 percent of the significant peaks (i.e. greater than 100,000 lbs) constitutes a good validation.

For the brake system, it is expected that TEDS should faithfully follow the brake application and release events in terms of timing and trend. If TEDS predicts that steady state (equalized) brake cylinder and brake pipe pressures are within 5 psi of the measured test values, that constitutes good validation. This variance is comparable to the Association of American Railroads (AAR)'s 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 the difference between the TEDS predictions and measured data might have a larger variation for brief periods as opposed to the 5 psi defined for the steady-state values.

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, would show a good correlation between the predicted and measured speed. TEDS has been carefully and methodically developed to meet these expectations. For validation purposes, it is expected that the TEDS predicted speed should be within 2 mph of the 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. Such an event occurs (criterion 1) with significant variation in force. It would also include a trend (criterion 2) 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 a time that corresponds to the handling change or a location that corresponds to the terrain change, depending on which feature resulted in the event. TEDS should predict that the trend of the event occurs in the same direction as in the measured data.

Predicting the magnitude of the event's parameter of interest (criterion 3) is the most difficult criterion to satisfy, due to the assumptions that are required to develop the model and linearizing (or piecewise linearization) of 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 summarizes the criteria for TEDS' validation.

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

Regime	Parameter	Criterion
Coupler Forces	Occurrence	Predict synchronization in timing and location
	Trend	Show correct trend
	Magnitude	Predict peaks (>100,000 lbs) within ±20 percent
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 ±2mph

3. Component Level Validation

The TEDS model contains the following components (or modules):

- air brake system
- coupler force system
- vehicle and train dynamics system

Initially, the first two components were validated separately from the other components before the overall results of the TEDS model were validated to decouple the validation effort and simplify the process of validation. The air brake system was decoupled from the vehicle and train dynamics because vehicle dynamics are independent from changes in air brake system pressure. Therefore the air brake system can be separately validated from the train and vehicle dynamics components. Since the coupler force system is decoupled from the air brake system when no air braking is occurring, the coupler force system can be separately validated from the other components.

3.1 Air Brake System

The air brake model in TEDS is a fluid mechanics-based mathematical model of air flow through the brake system of a train. The model represents the brake pipe, auxiliary and emergency reservoirs, control valve volumes and interconnecting passages, brake cylinders, and venting devices present on each rail car. The key quantities modeled include system pressures and air flows. The calculation procedure considers the brake pipe as discrete control volumes (of varying length) centered about each valve and venting device.

In this model, differential equations that govern mass and momentum conservation are solved simultaneously for the set of control volumes representing the brake pipe. Frictional effects such the resistance of the flow of air within the pipe and leakage from the pipe are also considered.

The control valve model includes the high-level modes that the valve operates in:

- Release and recharge
- Lap
- Application

The interconnection of reservoirs within a control valve is governed by pressure differences between reservoirs, the rate of brake pipe pressure reduction, and the previous state of the control valve. Modeled control valve states and functions include:

- Release and recharge
- Retarded recharge
- Preliminary quick service
- Quick service limiting

- Service
- Lap
- Emergency
- Accelerated emergency release
- Accelerated service release (ABD and later valves)
- Accelerated application (ABDW and later valves)

The air brake model can represent the interconnection of two or three reservoirs or volumes to calculate flows and pressure changes. Isothermal flow is assumed because the mass of air in the system is small compared to the mass of the reservoirs, cylinders, and the brake pipe itself and the small, transient fluctuations in air temperature are not significant to the train's braking performance.

Air brake test racks are used by the industry to evaluate and quantify the performance of control valves. In each rack, there is 50 feet of brake pipe, a 2,500 cubic inch auxiliary reservoir, and a 3,500 cubic inch emergency reservoir connected to each control valve. While any brake cylinder can be connected to the valves, typically a standard freight car brake cylinder with a 10-inch diameter and 8-inch stroke is utilized.

Published air brake test rack data, which is included in a paper from the 1986 Winter Meeting of the American Society of Mechanical Engineers (ASME) [1], shows data for a 50-car train equipped with ABDW valves during a full service application and a release from the full service application. An emergency application for a 150-car train is also presented. The air brake system component validation includes comparisons of model predictions with this data.

3.1.1 Full Service Application

A full-service application, using a 25 psig reduction, was made from a brake pipe pressure of 70 psig. Cars 1, 25, and 50 were reported in the test rack data. The test rack data was compared with the predictions of pipe pressure and brake cylinder pressure, as shown in Figure 3.1-1, Figure 3.1-2, and Figure 3.1-3. When TEDS predicted the final steady-state pressure for both the brake cylinder and the brake pipe, it matched the test rack data; the time at which full brake cylinder pressure is achieved for each car is matched very closely, along with the pressures in the upper half of the cylinder buildup. The cylinder pressure starts to increase at nearly the same time as the test rack data for all three cars.

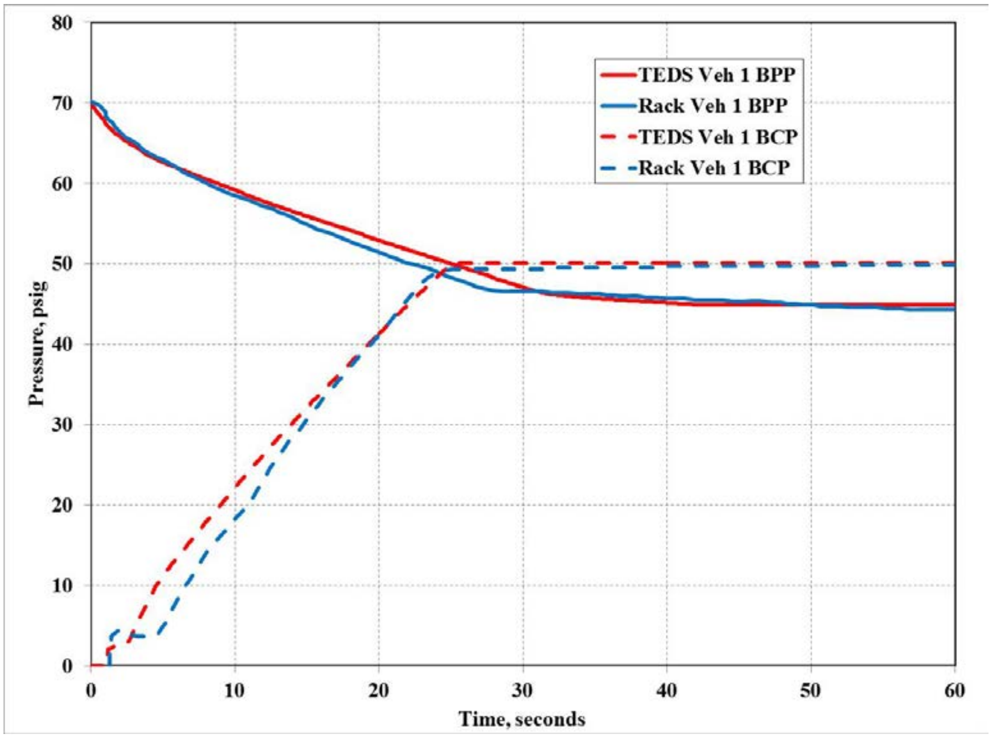


Figure 3.1-1. Comparison of test rack data and TEDS simulation for full service application, vehicle 1.

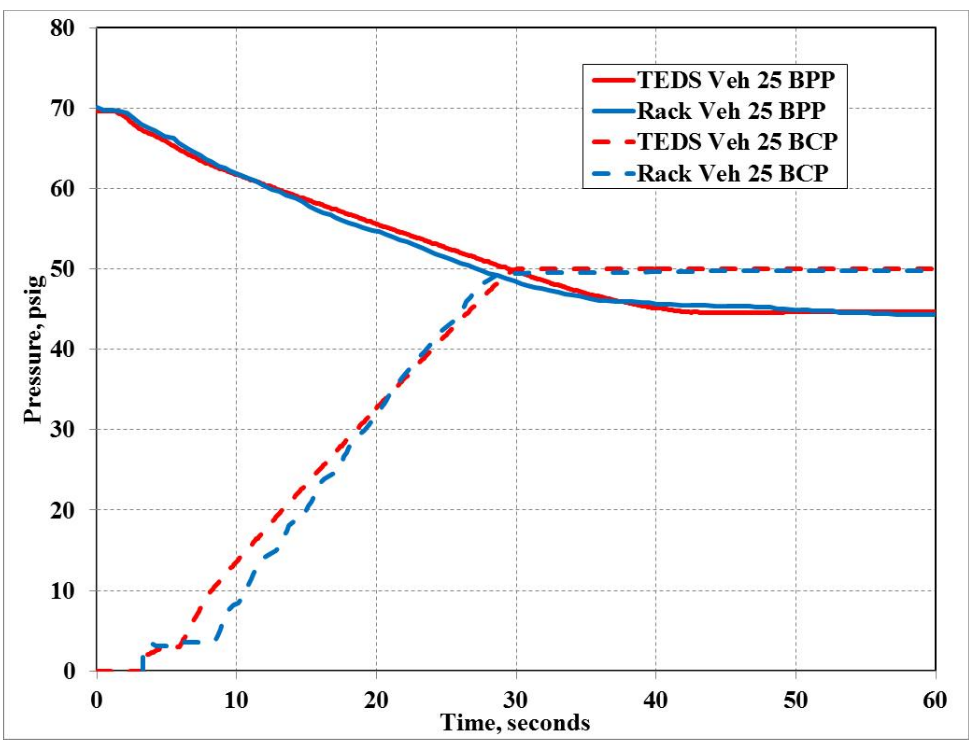


Figure 3.1-2. Comparison of test rack data and TEDS simulation for full service application, vehicle 25.

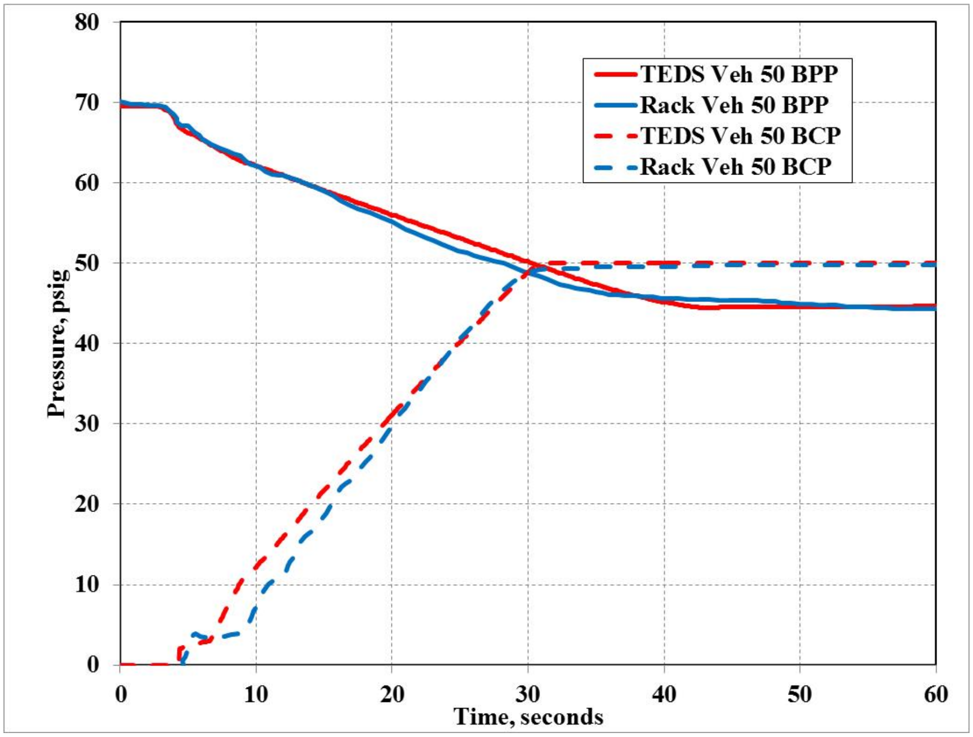


Figure 3.1-3. Comparison of test rack data and TEDS simulation for full service application, vehicle 50.

3.1.2 Release from Full Service Application

Data for a release from a full service application was taken from the 1986 ASME paper [1] (50-car test rack having 50 feet of brake pipe per car and all cars are equipped with ABDW valves). A TEDS simulation and the test rack data are compared for car 1 (Figure 3.1-4), for car 25 (Figure 3.1-5), and for car 50 (Figure 3.1-6). The brake pipe and brake cylinder pressures predicted by TEDS follow the trends in the test rack data very well, including the slight overshoot of pipe pressure at car 50, which is due to the reflection of the accelerated service release pressure wave at the closed end of the pipe.

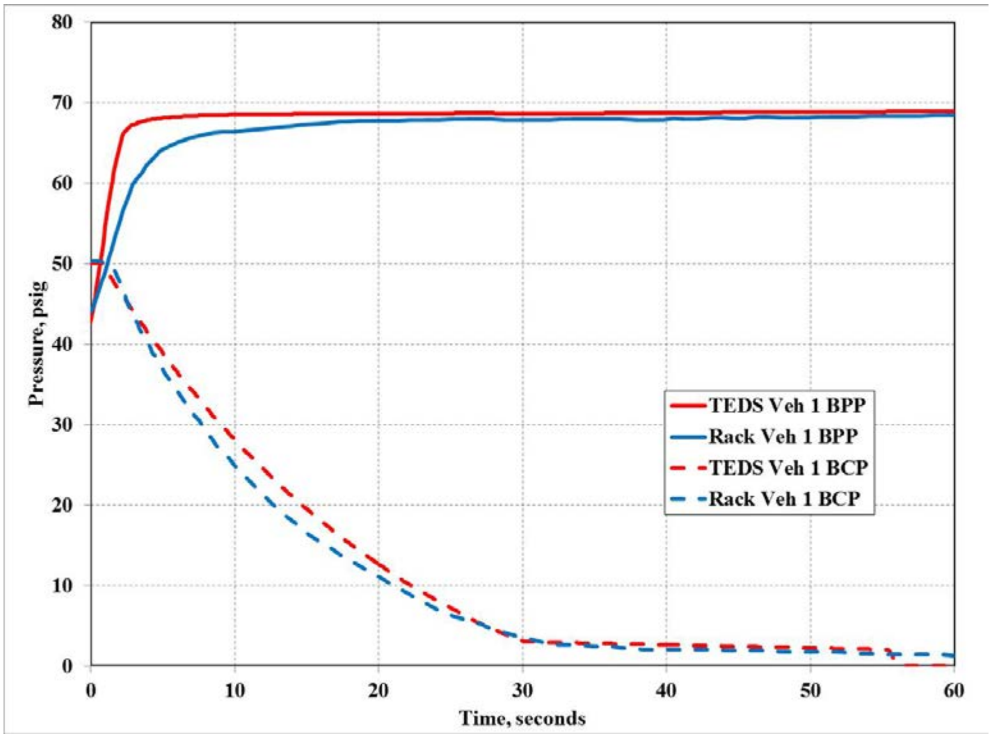


Figure 3.1-4. Comparison of test rack data and TEDS simulation for release from full service application, car 1.

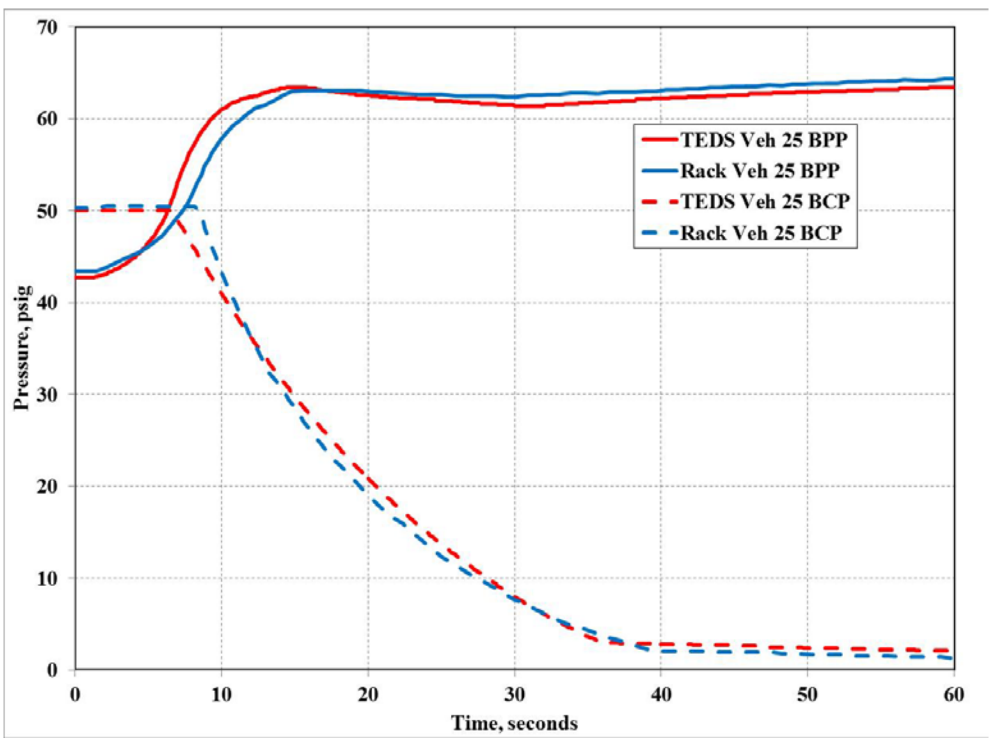


Figure 3.1-5. Comparison of test rack data and TEDS simulation for release from full service application, car 25.

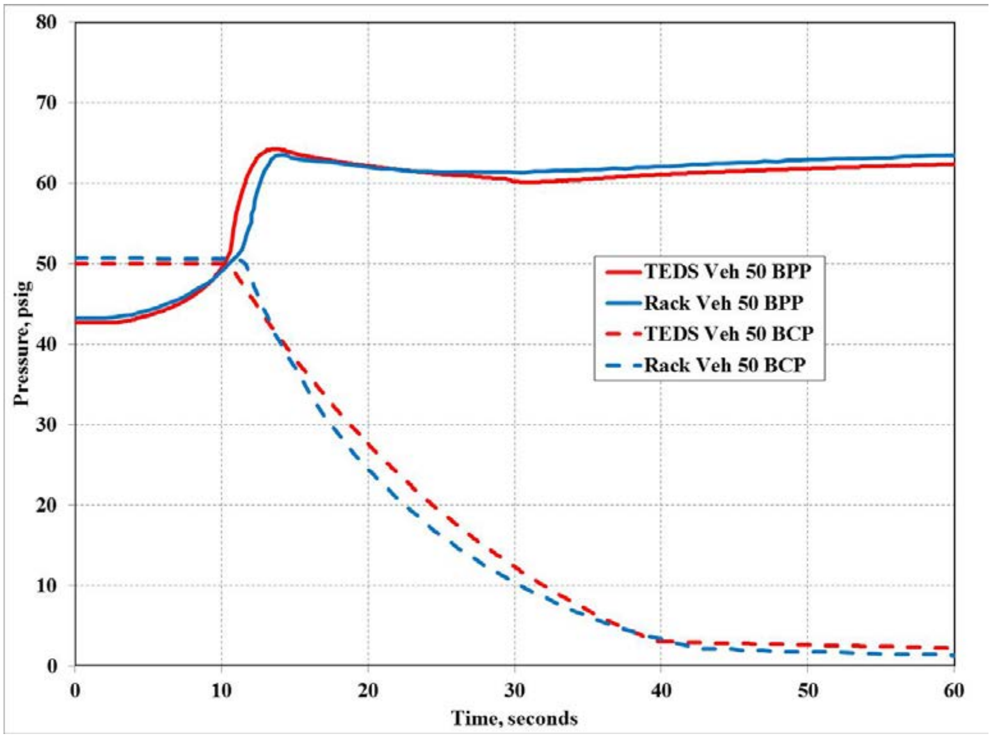


Figure 3.1. Comparison of test rack data and TEDS simulation for release from full service application, car 50.

3.1.3 Full Service Application with DB60L Valves

A second full service application was conducted on a test rack that was configured to simulate 25 cars (with 300 feet of brake pipe each) as a representation of 5-platform doublestack cars [2]. Each simulated car included two DB60L valves, one ABDW valve, and the regulating valve pressure setting was 90 psig. Figure 3.1-7 compares the TEDS simulation results with the test data for car 12 in the test rack. The predictions of the brake pipe pressure and cylinder pressure follow the test data very well. Also, Figure 3.1-8 compares simulation results for car 25 in the test rack, and again the predictions of brake pipe and brake cylinder pressure match the test data well.

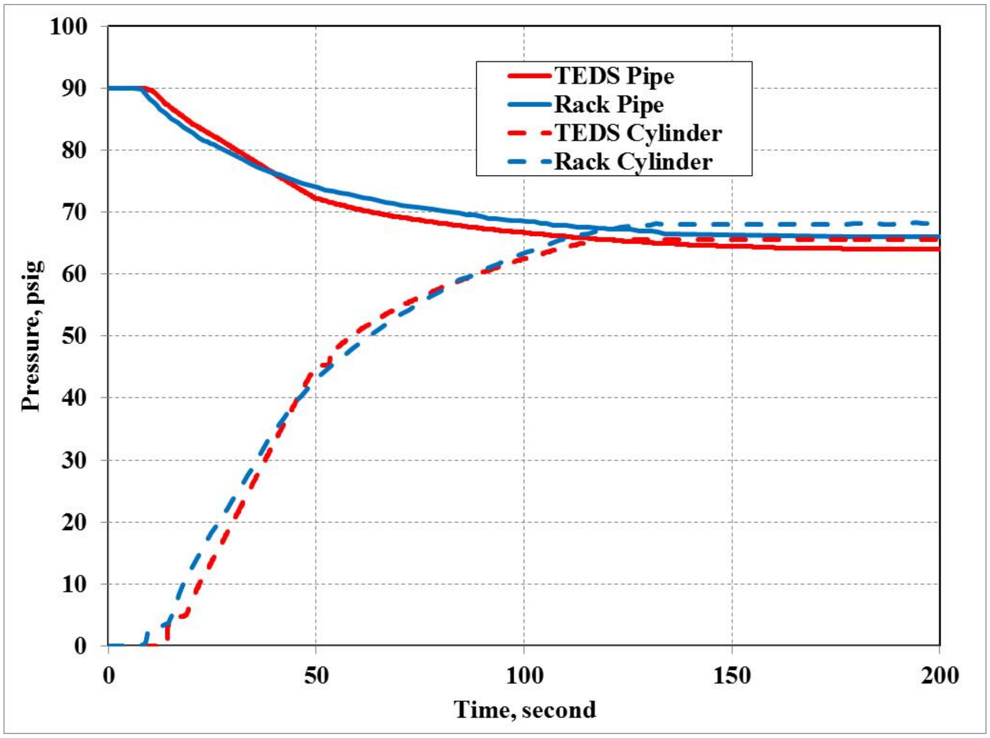


Figure 3.1-6. Comparison of test rack data and TEDS simulation of full service application on simulated 5-pack doublestack car 12.

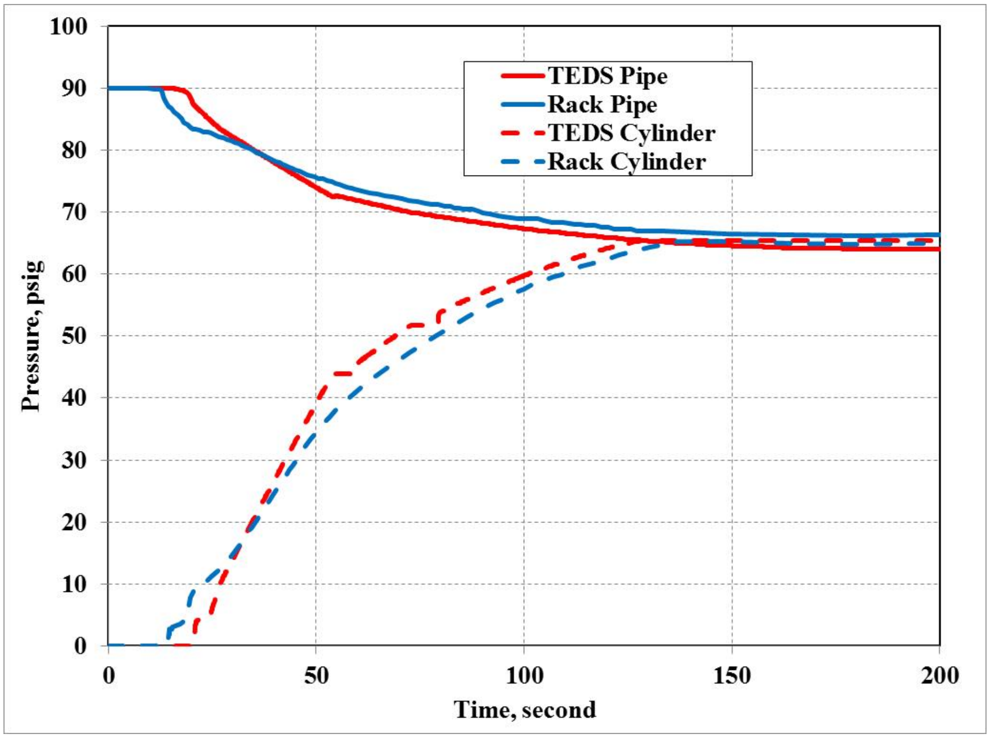


Figure 3.1-7. Comparison of test rack data and TEDS simulation of full service application on simulated 5-pack doublestack car 25.

3.1.4 Emergency Application

An engineer-initiated emergency was simulated on a 150-car train equipped with ABD valves with the regulating valve pressure setting at 80 psig. Figure 3.1-9 displays a comparison of the simulation with the test rack data. The TEDS simulation results match the slopes of the test rack data's brake pipe pressure drop and the brake cylinder pressure buildup well.

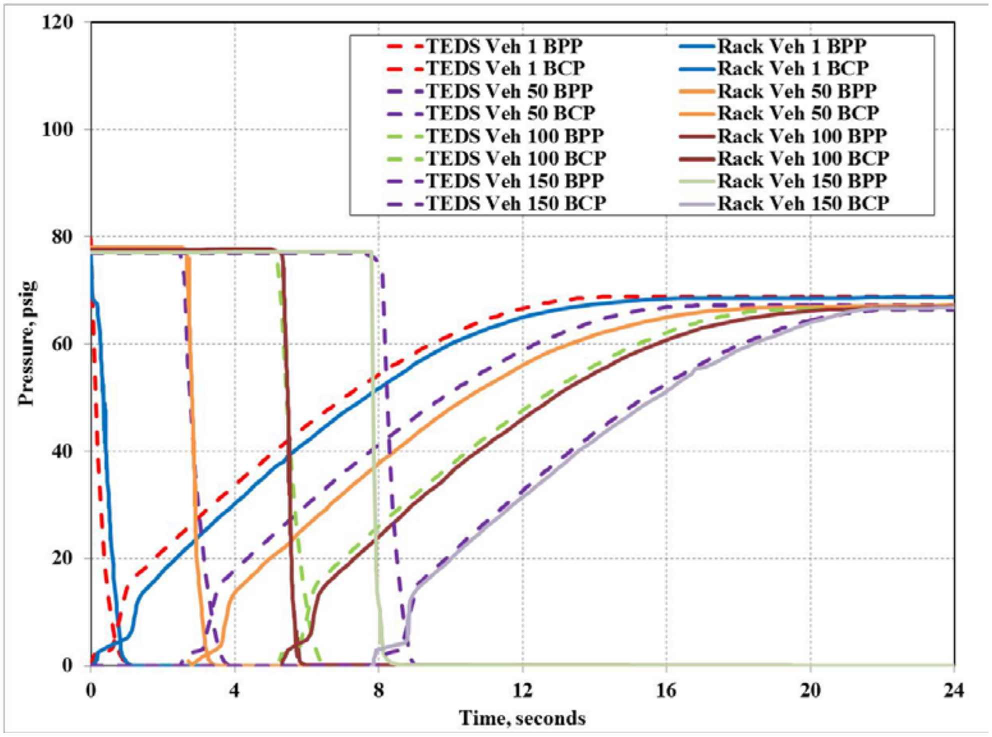


Figure 3.1-8. Comparison of test rack data and TEDS simulation of emergency application on 150-car train equipped with ABD valves.

3.1.5 ECP Brake Full Service and Release

Figure 3.1-10 and Figure 3.1-11 show comparisons of TEDS simulation results with measured test data from braking tests of a train made up of 156 ore cars retrofitted with ECP brakes [3] for a full service brake application and release on car 1 and car 156, respectively. The trends and magnitudes are matched closely by TEDS. The reservoir pressure does not drop nearly as much in an ECP train as in a conventional pneumatic train because the entire air supply in the ECP train is provided by a single reservoir with a volume of 6,000 cubic inches. The brake cylinder air for service applications in a conventional pneumatic train is provided by the auxiliary reservoir, which has a volume of 2,500 cubic inches. Thus, the pressure drops much less in the ECP train. When the reservoir pressure drops below a specified target in the ECP train, charging of the reservoirs by the brake pipe begins which causes the drop in brake pipe pressure.

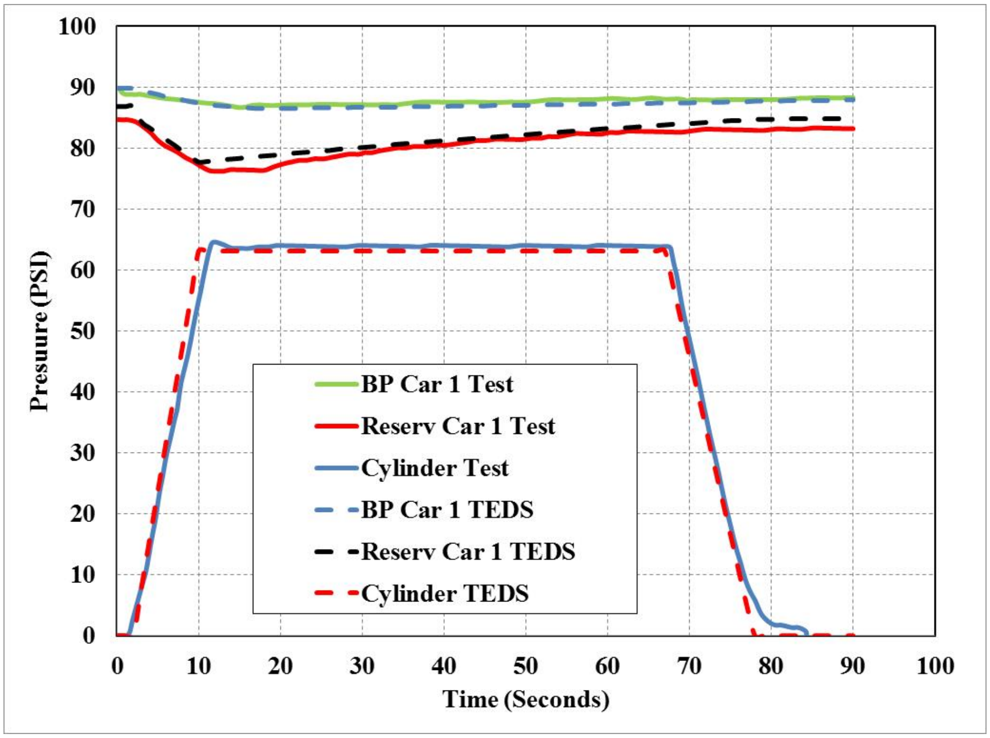


Figure 3.1-9. Comparison of TEDS simulation and measured test data for ECP brake reduction and release on car 1.

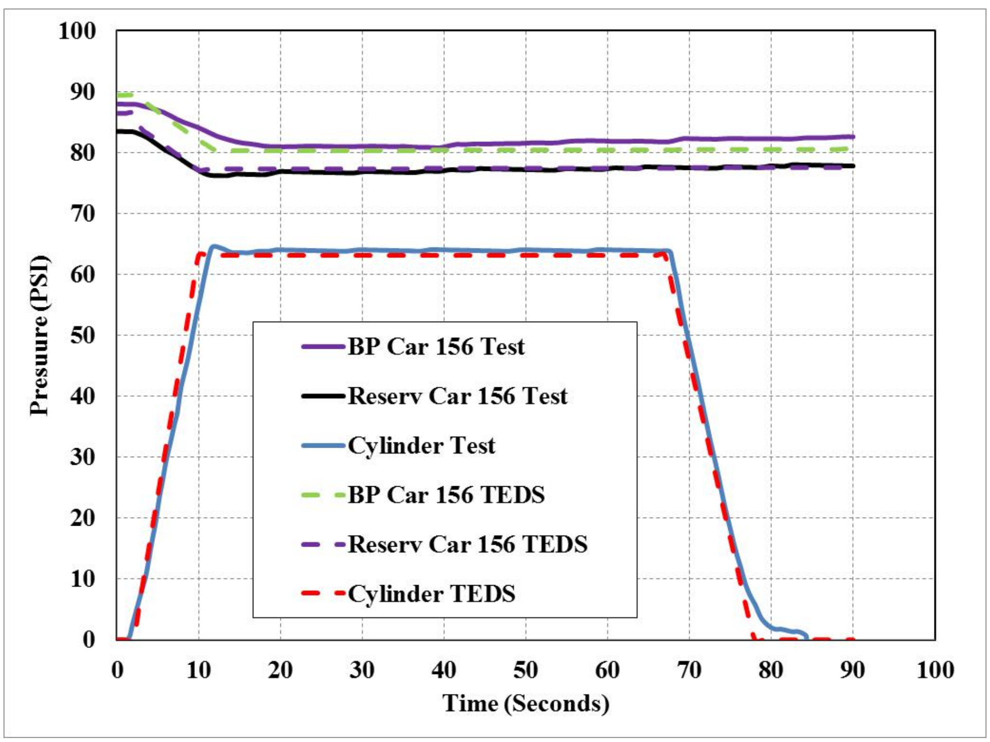
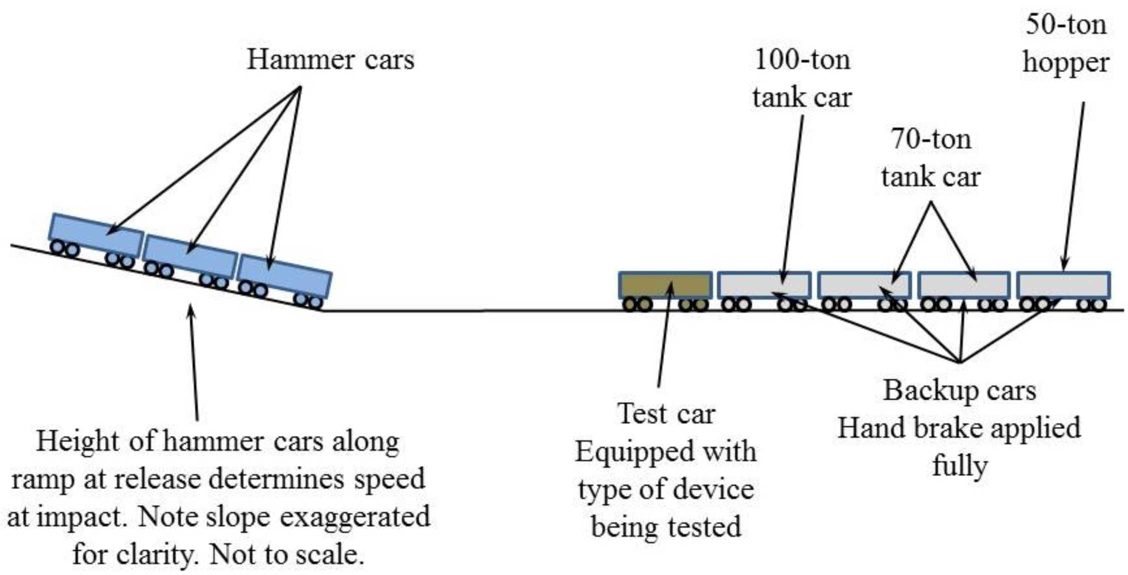


Figure 3.1-10. Comparison of TEDS simulation and measured test data for ECP brake reduction and release on car 156.

3.2 Coupler Force System

Coupler force model elements (such as draft gears and end-of-car cushioning units) are often tested, typically on an impact track. In such tests, several cars are placed at the bottom of the ramp. The first car in the string is called the anvil car (test car) and is struck by the moving (or hammer) cars. The string of cars behind the anvil car are called the “backup cars.” The anvil car is equipped with the element being tested. The testing conducted by the AAR [4] included three hammer cars in the moving string. All of the hand brakes on the backup cars were fully applied. The target speed for this particular test governs the location along the ramp from which the car is released. A higher release location results in a greater speed. The impact test setup is shown in Figure 3.2-1. Coupler force and travel were recorded and cross-plotted to show the force-stroke characteristics.



Draft gear and end-of-car cushioning unit impact test setup.

3.2.1 Friction Draft Gear

Metal friction draft gears were testing the impact test arrangement shown (Figure 3.2-1). Figure 3.2-2) shows the results at several test speeds. The figure shows some of the variability in the test data and the difficulty in precisely matching the measured characteristics at all speeds.

Figure 3.2-3 compares the measured test data of coupler force and stroke for a 2.05 mph impact with the TEDS predictions, and Figure 3.2-4 shows the comparison for a 3.90 mph impact. The predictions follow the test data very well in both cases.

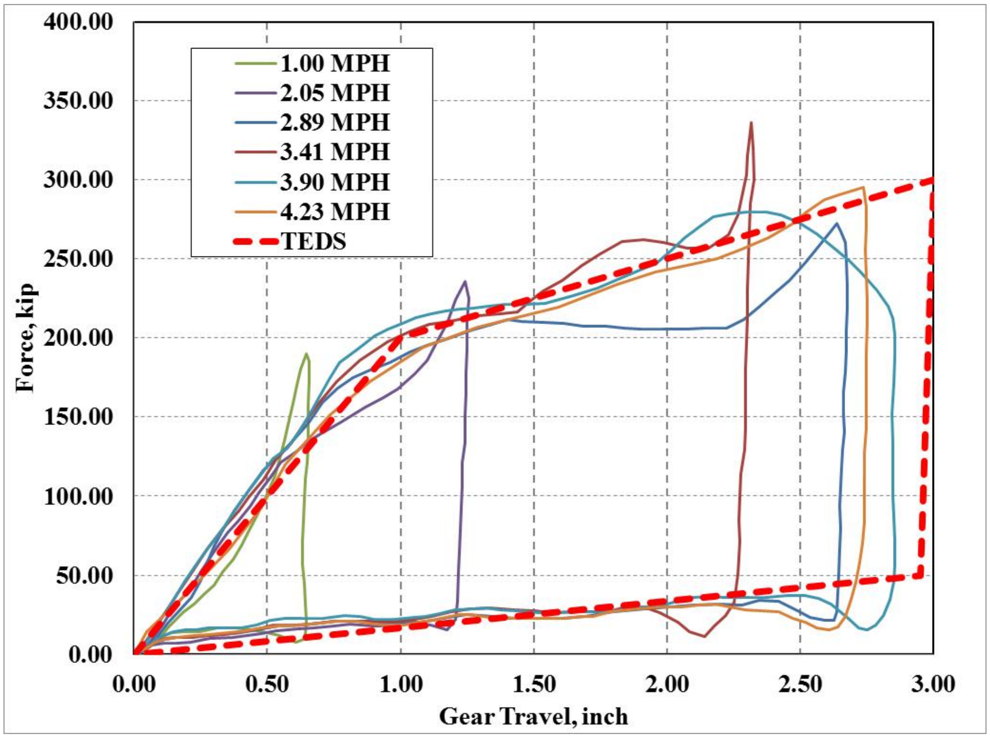


Figure 3.2-1. Overlay of multiple speeds tested for metal friction draft gear.

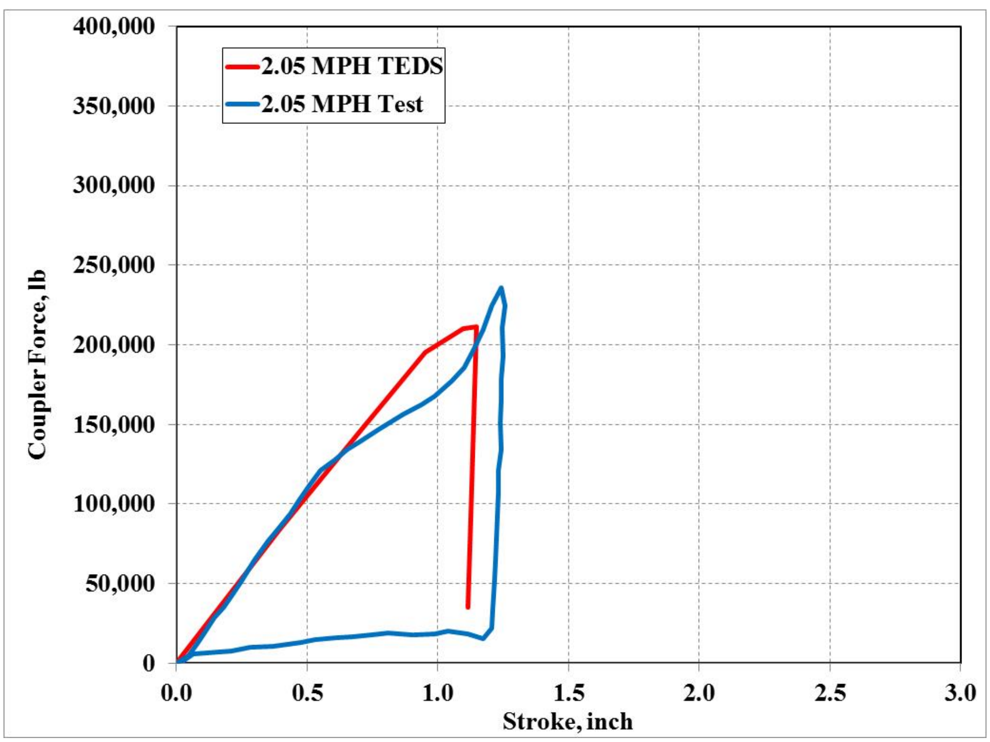


Figure 3.2-2. Metal friction draft gear force-stroke comparison at 2.05 MPH impact.

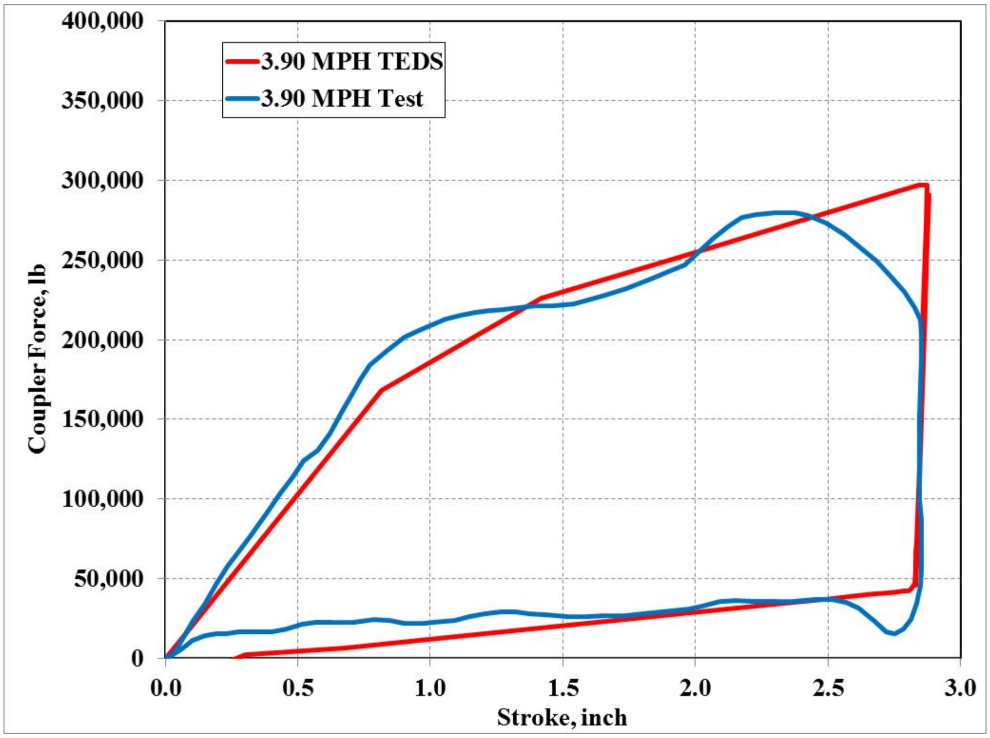


Figure 3.2-3. Metal friction draft gear force-stroke comparison at 3.90 MPH impact.

3.2.2 Rubber Friction Draft Gear

Rubber draft gears were also characterized at several speeds using the impact test setup shown in Figure 3.2-1. Figure 3.2-5 shows the force-stroke characteristics for several speeds tested for the rubber draft gear.

Figure 3.2-6 compares the measured test data for a 1.18 mph impact with the TEDS predictions and Figure 3.2-7 shows the comparison for a 3.94 mph impact. The TEDS predictions match the measured test data well in both cases.

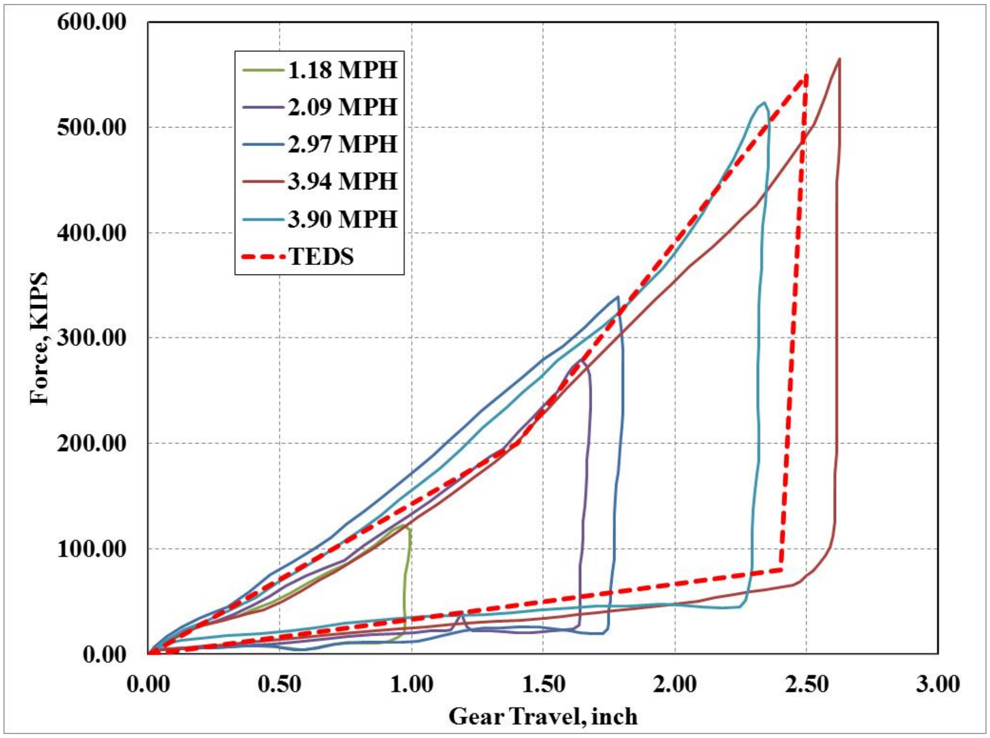


Figure 3.2-4. Overlay of multiple speeds tested for rubber draft gear.

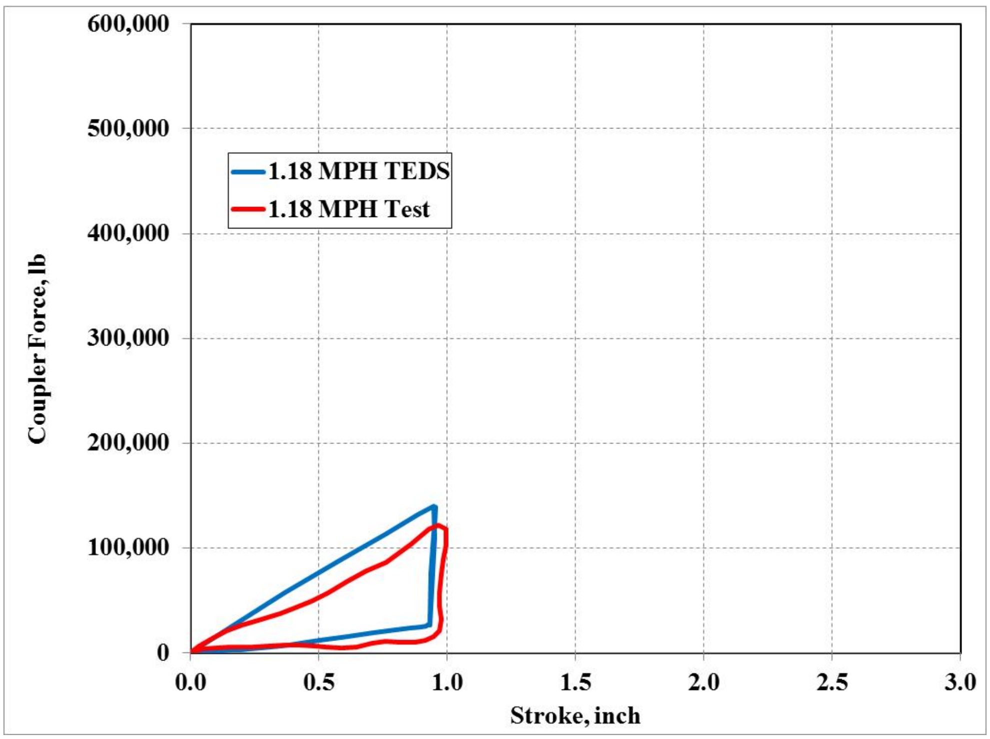


Figure 3.2-5. Rubber draft gear force-stroke comparison at 1.18 MPH impact.

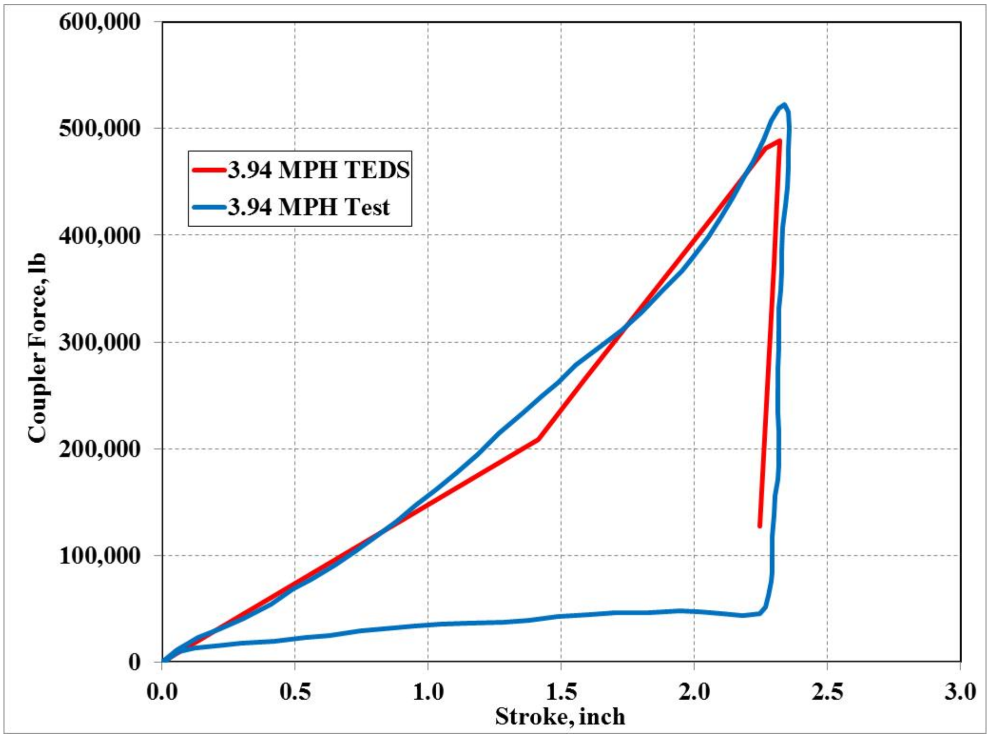


Figure 3.2-6. Rubber draft gear force-stroke comparison at 3.94 MPH impact.

4. System Level Validation

4.1 Air Brake System

A unit coal train's air brake data from a full service reduction was presented at an American Society of Mechanical Engineers – Rail Technology Division meeting in October 1992 [5]. The train included 99 cars and six locomotives, with four locomotives located at the head end and the remaining two locomotives placed near the middle of the train. The remote units were not charging the brake pipe, although the application was initiated from both the lead and remote sets of locomotives. The regulating valve setting was 100 psig. The application was not typical because shortly after the initial partial application, a release was made. This was followed by a full service reduction.

The following figures compare the TEDS predictions of brake pipe and brake cylinder pressure with the four cars that were instrumented for data collection: Figure 4.1-1 for car 1, Figure 4.1-2 for car 17, Figure 4.1-3 for car 57, and Figure 4.1-4 for car 77. For all four cars, the trend and magnitude of the predicted brake pipe pressure follows the measured data very well.

The brake cylinder pressure trends generated by the data are followed very well by TEDS for all four cars. The predicted brake cylinder pressure magnitudes are also fairly close to the measured data. Minor differences in the final cylinder pressure may be due to slight cylinder volume differences. Cylinder pressures that change significantly after the pipe pressure has stabilized, such as in Figure 4.1-2 and Figure 4.1-3, are not completely understood and could be due to measurement drift, or leakage in the valve through an incompletely closed port between the auxiliary reservoir and the brake cylinder. Overall, the match between the TEDS predictions and the measured test data was very good.

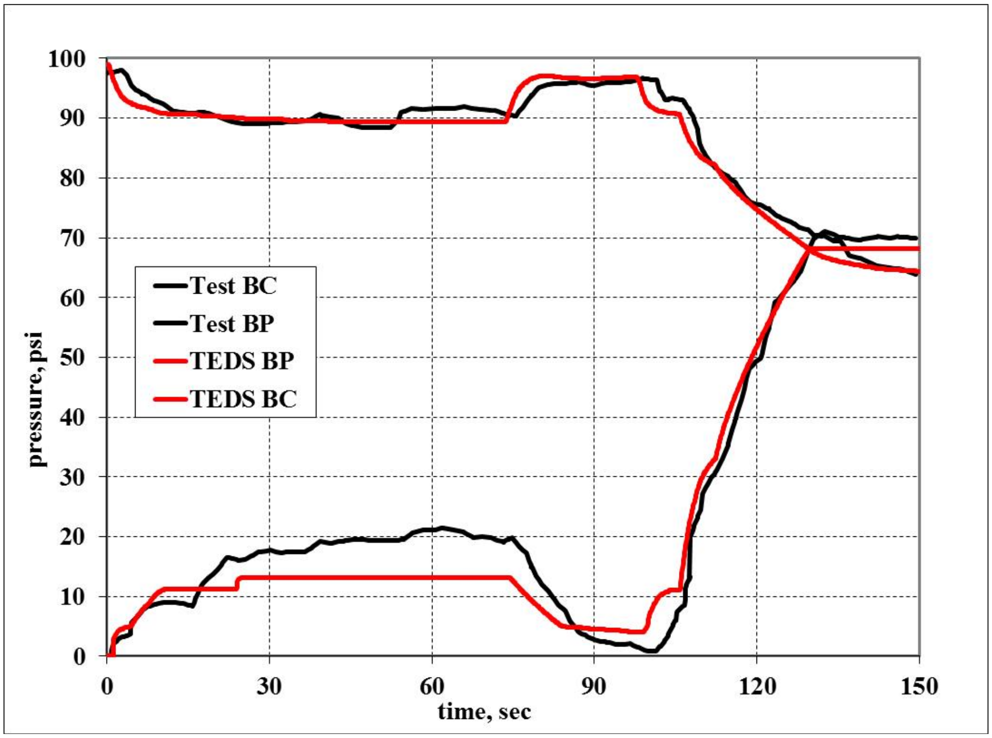


Figure 4.1-1. Comparison of brake pipe and brake cylinder pressures on car 1 on the unit coal train.

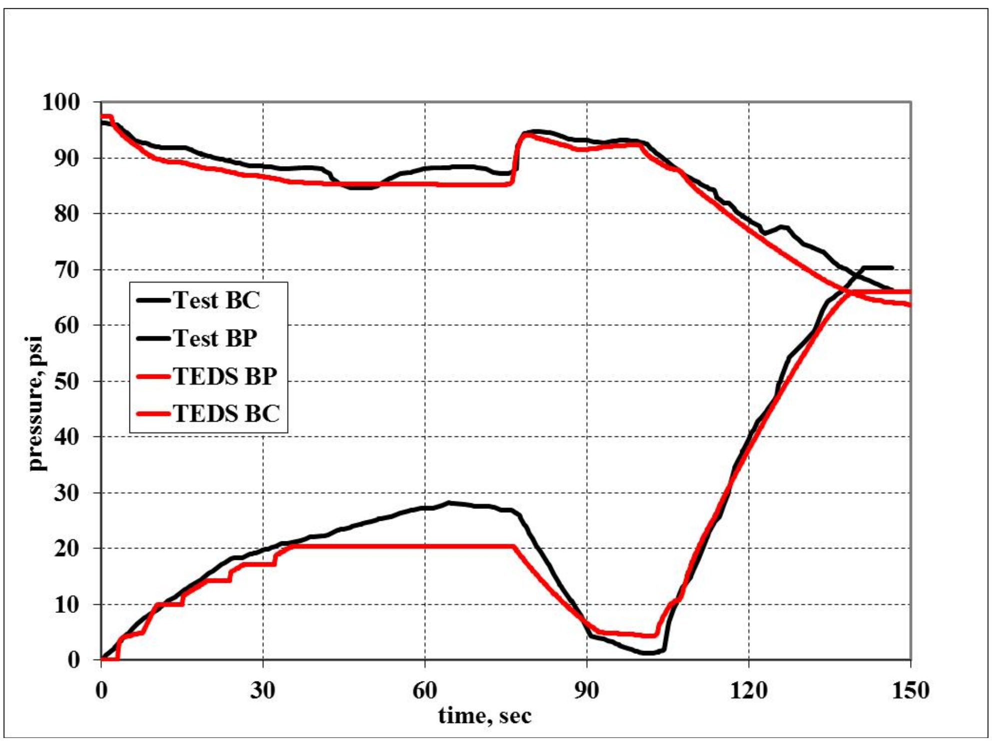


Figure 4.1-2. Comparison of brake pipe and brake cylinder pressures on car 17 on the unit coal train.

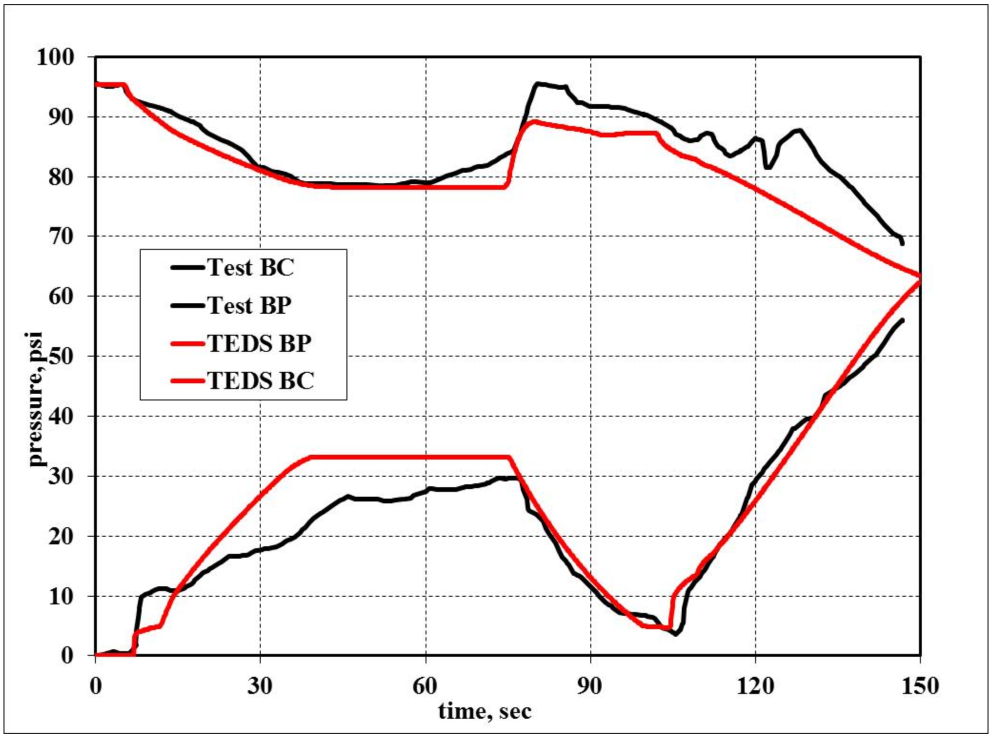


Figure 4.1-3. Comparison of brake pipe and brake cylinder pressures on car 57 on the unit coal train.

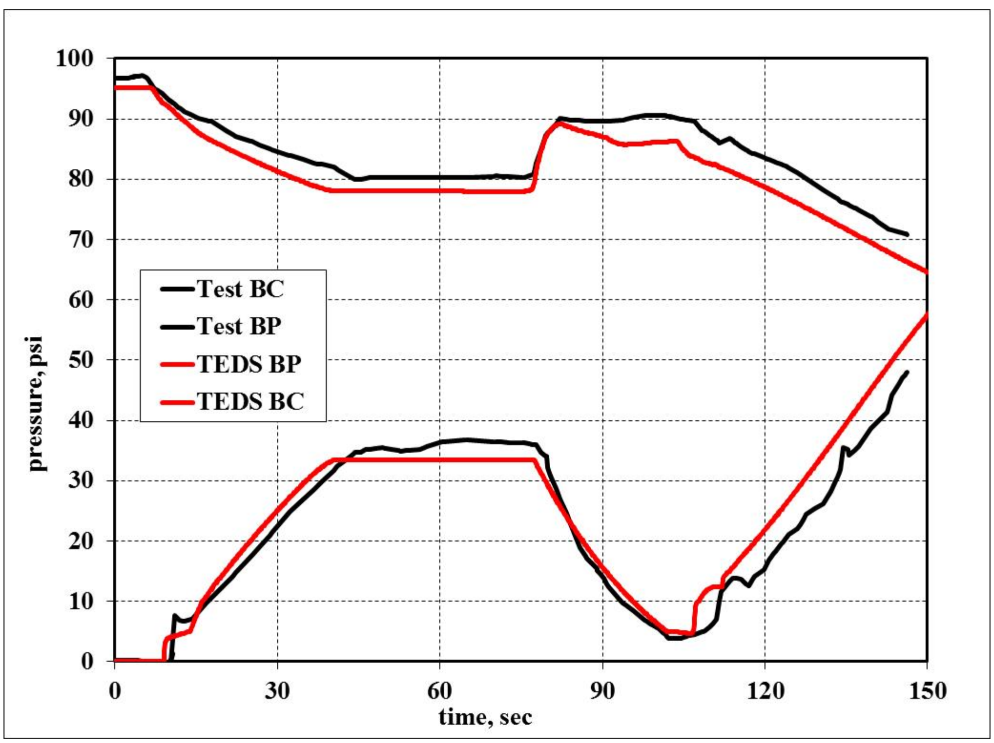


Figure 4.1-4. Comparison of brake pipe and brake cylinder pressures on car 77 on the unit coal train.

4.2 Train Speed

When the National Transportation Safety Board (NTSB) investigates a train incident, it gathers all pertinent data on the accident, which includes complete train information, track data around the incident site, and train handling data from the event recorders. Once NTSB publishes its final report, all this data is available to the public NTSB docket sites.

To validate TEDS' ability to predict train speeds, incidents from the NTSB docket where the track data includes several miles preceding the event were chosen. These cases were selected since they had been simulated at the behest of NTSB during its evaluation of TEDS as a potential investigative support tool. The trains involved in these events were simulated with TEDS and those results were compared to the event recorder speed.

4.2.1 Simulation of Train Approaching Tiskilwa, IL

The Tiskilwa, IL incident is documented in a NTSB docket [6]. Twenty six (26) cars were derailed in this incident, releasing some hazardous material and requiring evacuation of nearby residents.

A summary of the train in the Tiskilwa, IL incident is shown in Table 4.2-1. All locomotives are at the head end of the train. The weight and length distributions are shown in Figure 4.2-1 and Figure 4.2-2, respectively. The car lengths and weights are fairly uniform except for the three empty cars in vehicle positions 84-86. The track chart for this scenario is shown in Figure 4.2-3. The segment simulated is entirely descending grade. The train was simulated for approximately 9 miles.

The train handling and speed for this scenario is shown in Figure 4.2-4. The train handling varies between notch 2 and dynamic 5. The event recorder only stores the locomotive speed to the nearest integer value. Therefore, the reported speed from the event recorder (the black curve) shows jumps in value at several locations. The lead locomotive speed from the TEDS simulation shown in the red curve in Figure 4.2-4 matches the event recorder speed very well.

Table 4.2-1. Tiskilwa, IL train summary.

No. of Locomotives	Head-end	2
	Middle	0
	Remote/Rear	0
Total Horsepower		8,800
No. of Cars	Total	131
	Empty	3
	Loaded	128
Trailing Tons		16,350
Total Tons		16,780
Horsepower/Ton		0.538
Train Length (Including Locomotives) in feet		8,156

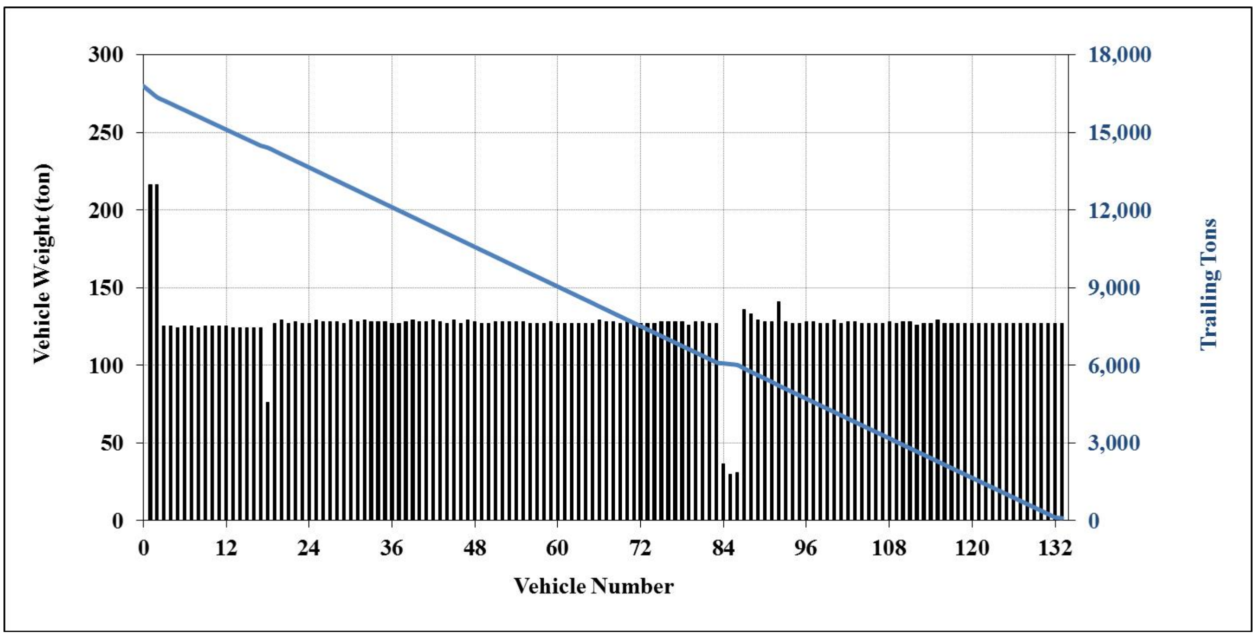


Figure 4.2-1. Tiskilwa, IL train weight distribution.

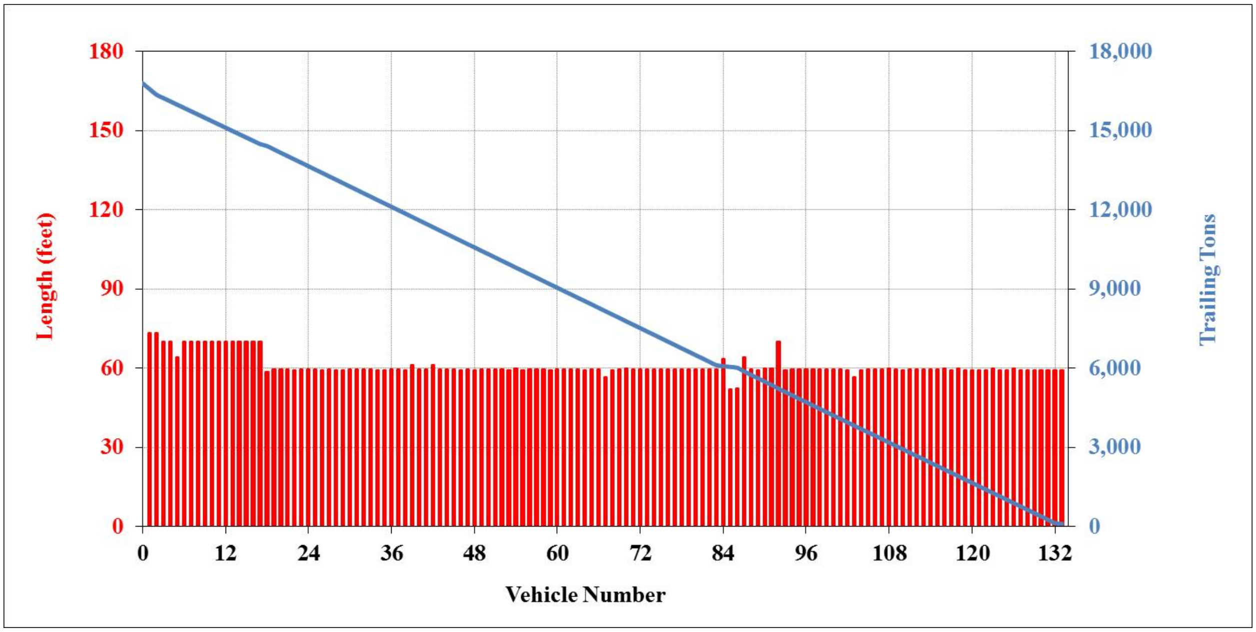


Figure 4.2-2. Tiskilwa, IL train length distribution.

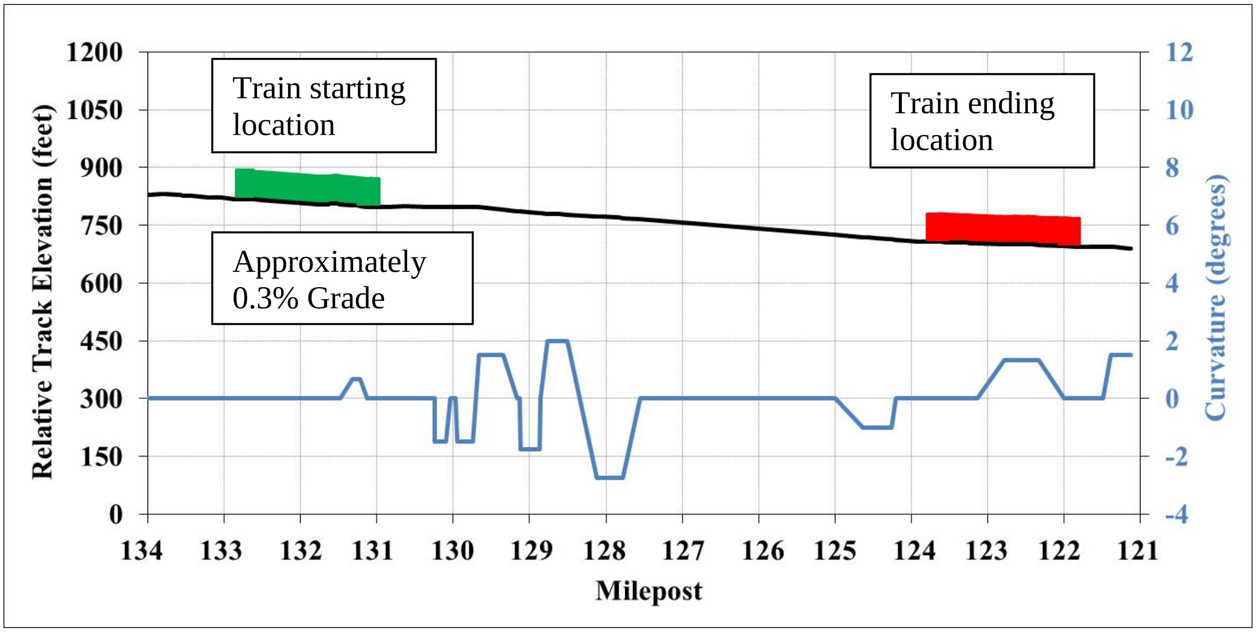


Figure 4.2-3. Tiskilwa, IL track chart. The train was simulated for approximately 9 miles.

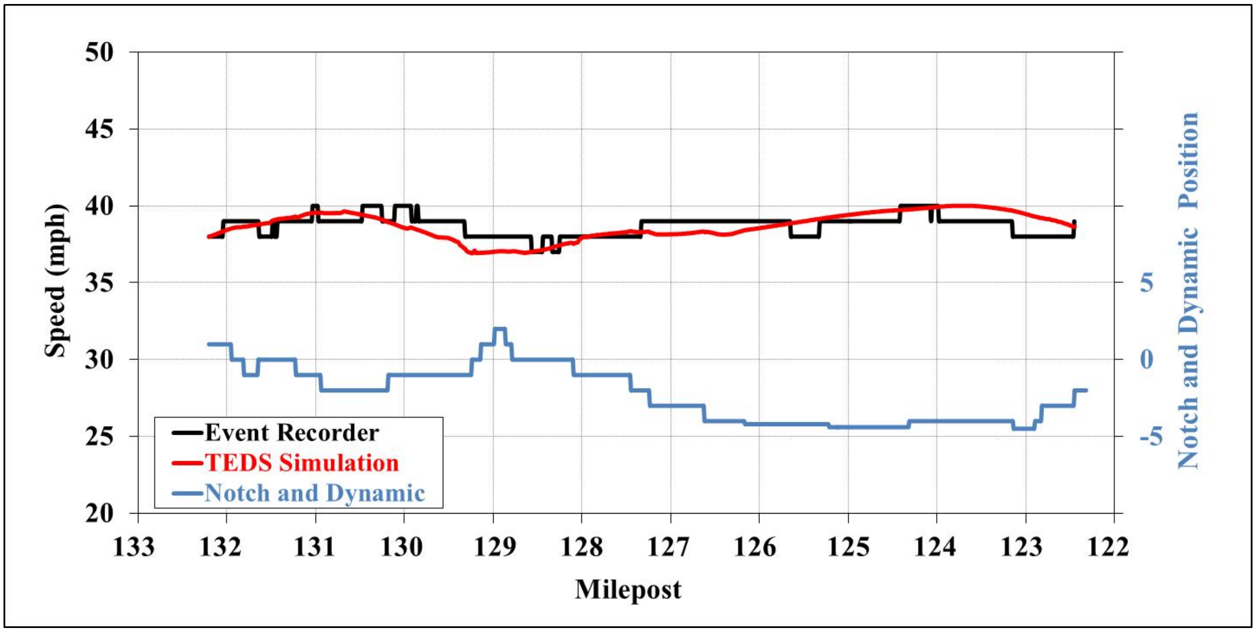


Figure 4.2-4. Train handling and comparison of simulated and event recorder speed.

4.2.2 Simulation of Train Approaching Red Oak, IA

In the Red Oak, IA incident, a loaded coal train collided with the rear end of a maintenance-of-way train, which caused the derailment of two locomotives and twelve cars [7].

A summary of the train in the Red Oak, IA incident is given in Table 4.2-2. One locomotive was located at the end of the train and was operated remotely while the remaining two locomotives were located at the head end. The weight and length distributions are shown in Figure 4.2-5 and Figure 4.2-6, respectively. The car lengths and weights are fairly uniform throughout the train. The track chart for this scenario is shown in Figure 4.2-7. The terrain here is entirely ascending grade. The train was simulated for approximately 9 miles.

The train handling and speed for this scenario is shown in Figure 4.2-8. The train handling varied between notch 8 and dynamic 8 for the entire ascending grade route. The event recorder only stored the locomotive speed to the nearest integer value. Therefore the reported speed from the event recorder (the black curve) shows stairstepping throughout the run. The lead locomotive speed from the TEDS simulation shown in the red curve in Figure 4.2-8 matches the event recorder speed very well.

Table 4.2-2. Red Oak, IA train summary.

No. of Locomotives	Head-end	2
	Middle	0
	Remote/Rear	1
Total Horsepower		17000
No. of Cars	Total	130
	Empty	0
	Loaded	130
Trailing Tons		18,529
Total Tons		19,159
Horsepower/Ton		0.89
Train Length (Including Locomotives), ft		7,122

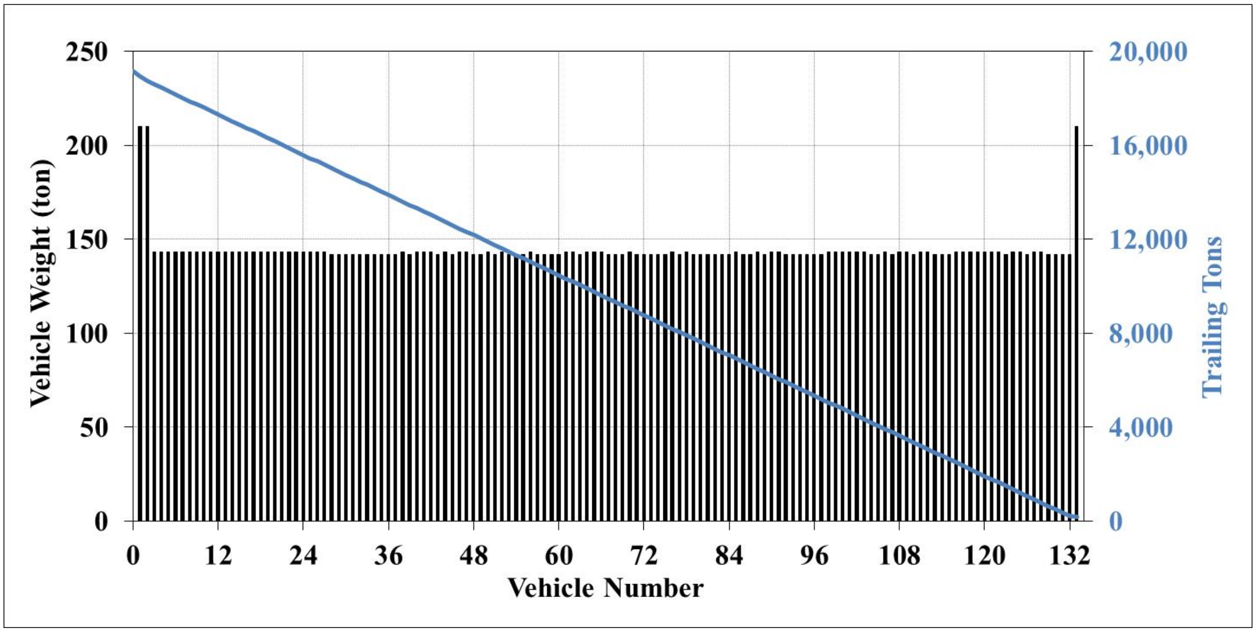


Figure 4.2-5. Red Oak, IA train weight distribution.

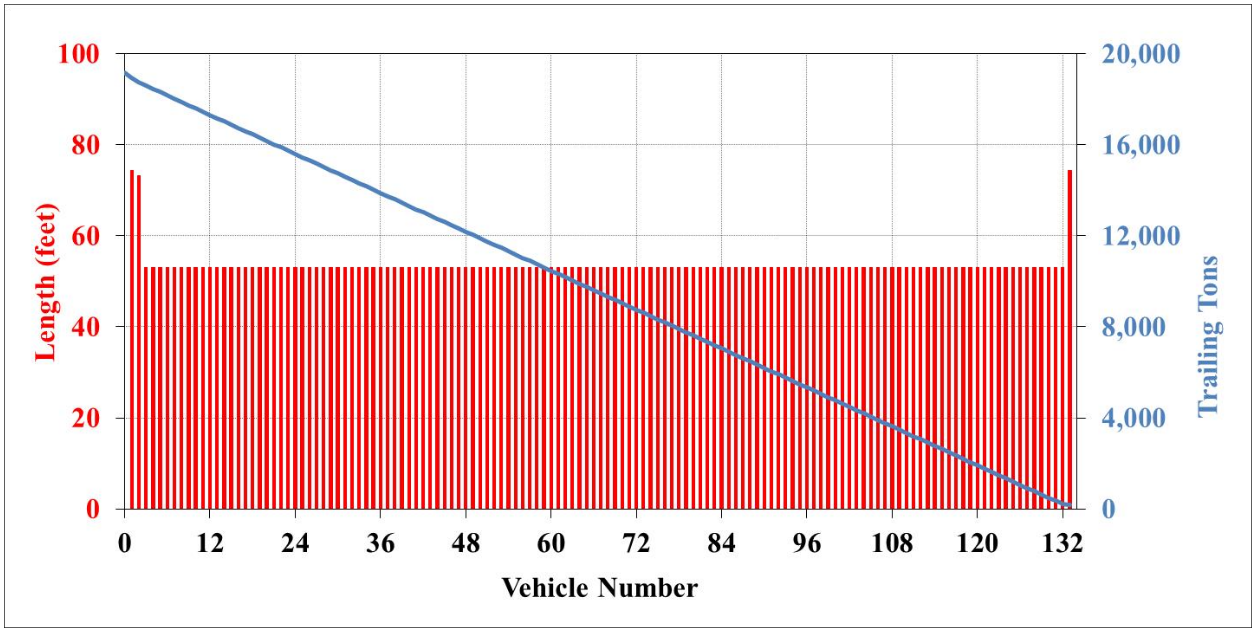


Figure 4.2-6. Red Oak, IA train length distribution.

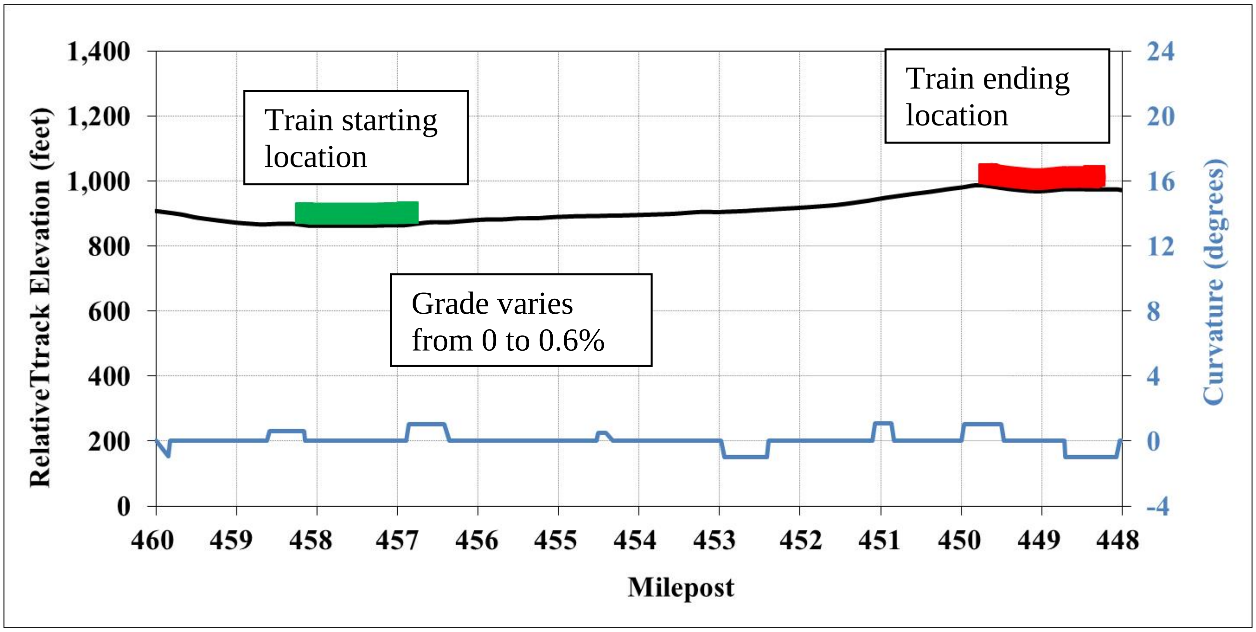


Figure 4.2-7. Red Oak, IA track chart.

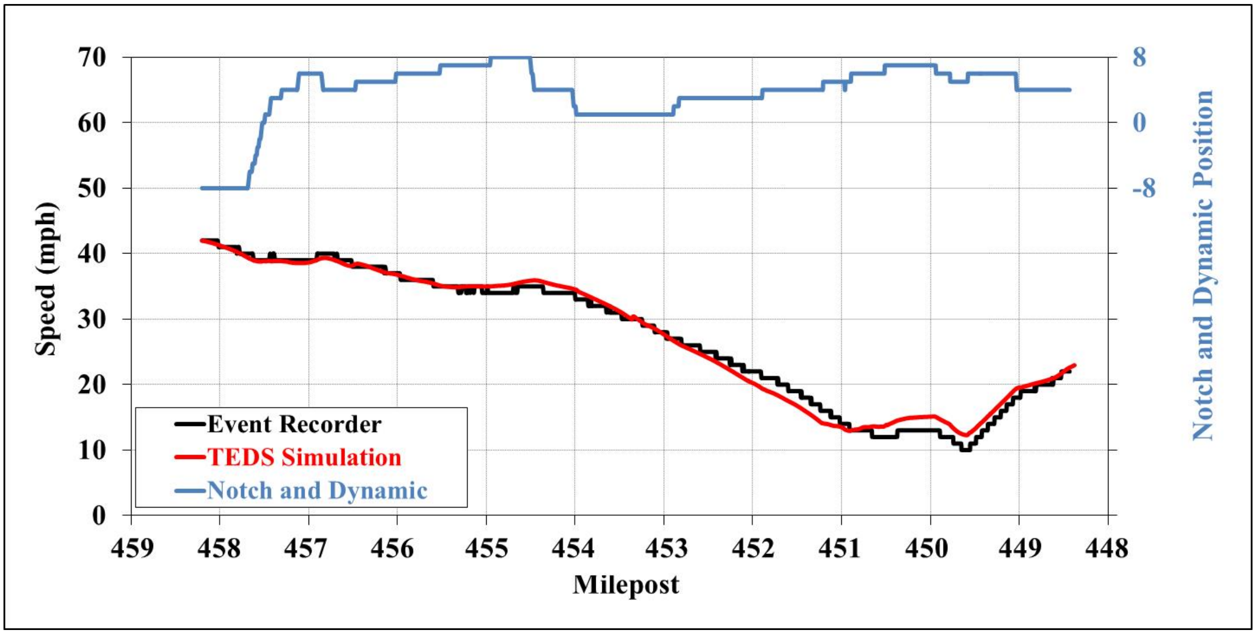


Figure 4.2-8. Red Oak, IA train handling and speed comparison.

4.2.3 Simulation of Westbound Train Approaching Goodwell, OK

In the Goodwell, OK incident, two mixed freight trains were in a head-on collision [8]. The summary of the westbound train in the Goodwell, OK event is shown in Table 4.2-3. One locomotive was located at the rear of the train and operated remotely. The remaining two locomotives were located at the head end of the train. The weight and length distributions are shown in Figure 4.2-9 and Figure 4.2-10, respectively. The car lengths and weights are fairly uniform throughout the train. The track chart for this scenario is shown in Figure 4.2-11. The terrain here is entirely ascending grade. The train was simulated for approximately 55 miles.

The train handling and speed for this scenario is shown in Figure 4.2-12. The train handling varied between notch 8 and idle for the entire ascending grade route. The event recorder only stored the locomotive speed to the nearest integer value. Therefore, the reported speed from the event recorder (the black curve) shows stairstepping throughout the run. The lead locomotive speed from the TEDS simulation shown in the red curve in Figure 4.2-12 matches the event recorder speed very well.

Table 4.2-3. Westbound Goodwell, OK train summary.

No. of Locomotives	Head-end	2
	Middle	0
	Remote/Rear	1
Total Horsepower		12,690
No. of Cars	Total	80
	Empty	0
	Loaded	80
Trailing Tons		5,759
Total Tons		6,389
Horsepower/Ton		1.98
Train Length (Including Locomotives) in feet		7,742

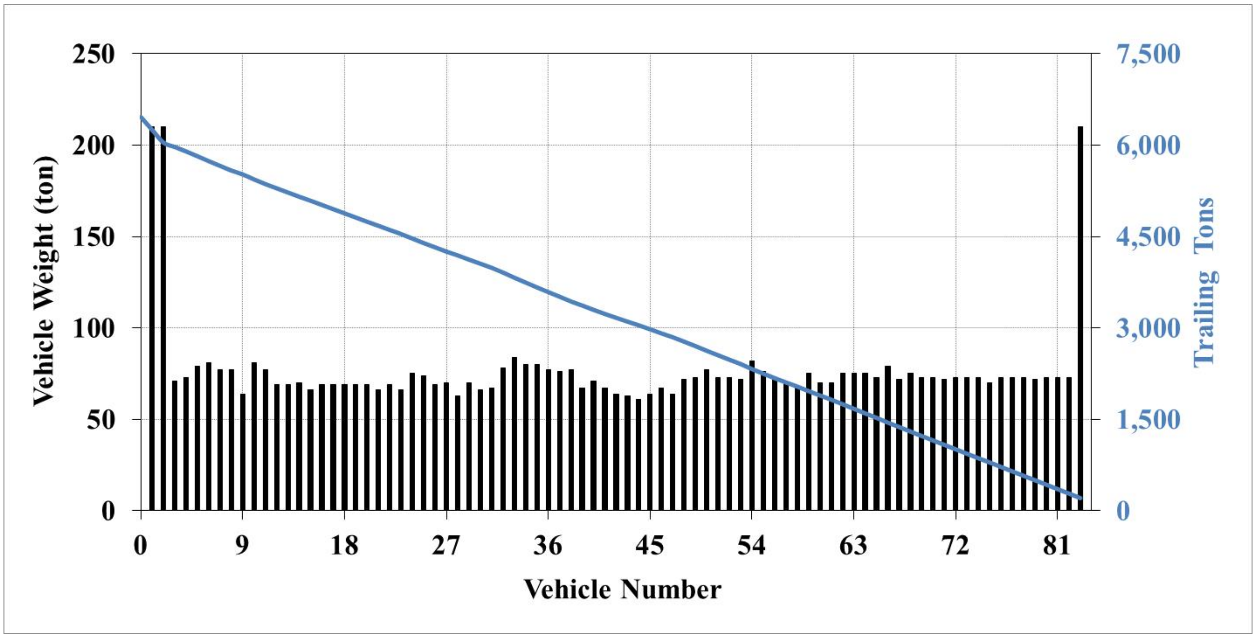


Figure 4.2-9. Westbound Goodwell, OK train weight distribution.

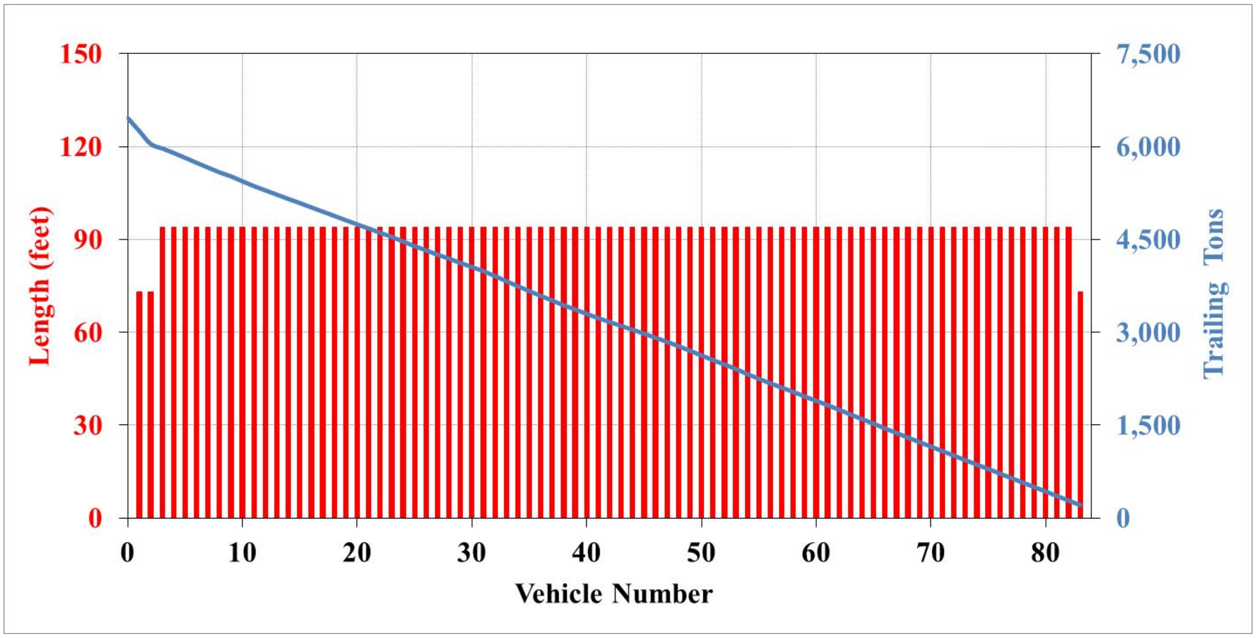


Figure 4.2-10. Westbound Goodwell, OK train length distribution.

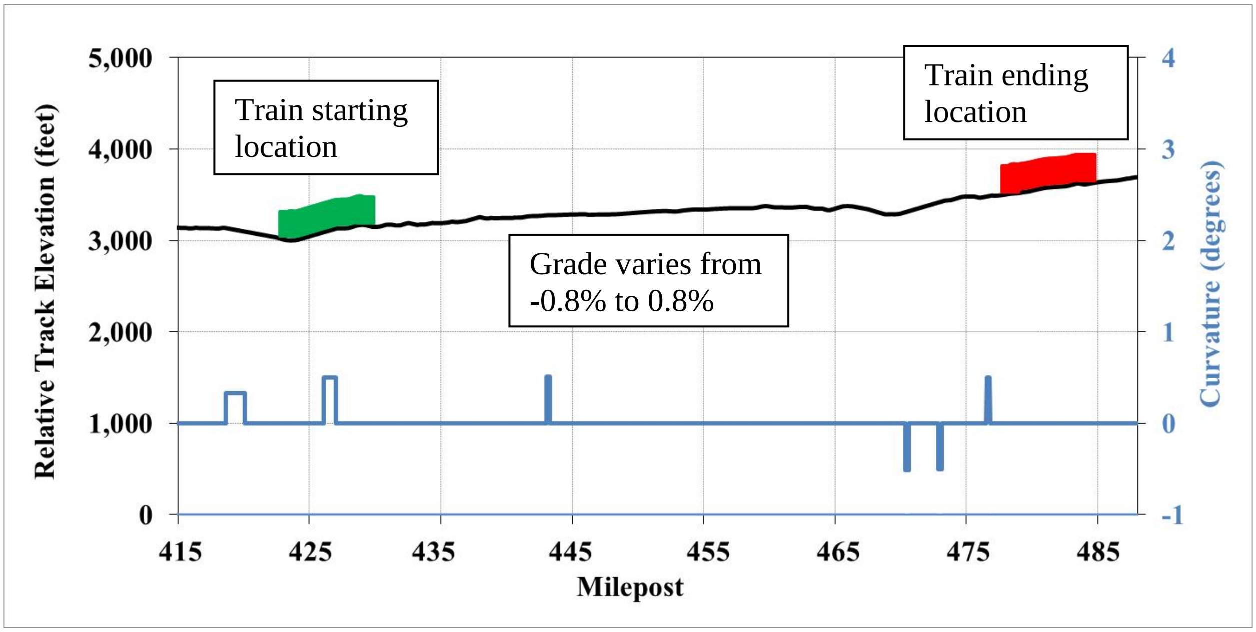


Figure 4.2-11. Westbound Goodwell, OK track chart.

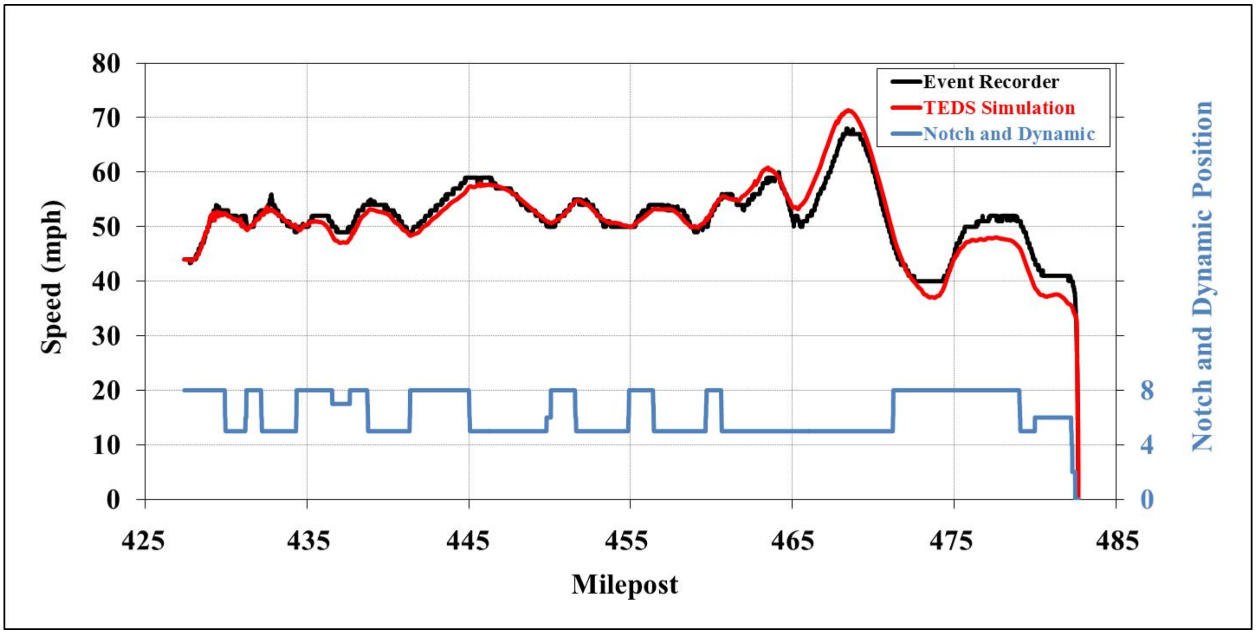


Figure 4.2-12. Westbound Goodwell, OK train handling and speed comparison.

4.2.4 Simulation of Eastbound Train Approaching Goodwell, OK

In the Goodwell, OK incident, two mixed freight trains were in a head-on collision [8]. The summary of the eastbound train in the Goodwell, OK event is shown in Table 4.2-4.

Two locomotives were at the head end of the train while the third locomotive was at the rear of the train and operated remotely. The weight and length distributions are shown in Figure 4.2-13 and Figure 4.2-14, respectively. The car lengths and weights are fairly uniform throughout the train. The track chart for this scenario is shown in Figure 4.2-15. The terrain here is entirely descending grade. The train was simulated for approximately 30 miles.

The train handling and speed for this scenario is shown in Figure 4.2-16. The train handling varied between notch 8 and dynamic 8 for the entire descending grade route. The event recorder only stored the locomotive speed to the nearest integer value. Therefore the reported speed from the event recorder (the black curve) shows stairstepping throughout the run. The lead locomotive speed from the TEDS simulation shown in the red curve in Figure 4.2-16 matches the event recorder speed very well.

Table 4.2-4. Eastbound Goodwell, OK train summary.

No. of Locomotives	Head-end	3
	Middle	0
	Remote/Rear	1
Total Horsepower		17,500
No. of Cars	Total	108
	Empty	0
	Loaded	108
Trailing Tons		6,330
Total Tons		7,188
Horsepower/Ton		2.43
Train Length (Including Locomotives) in feet		7919.5

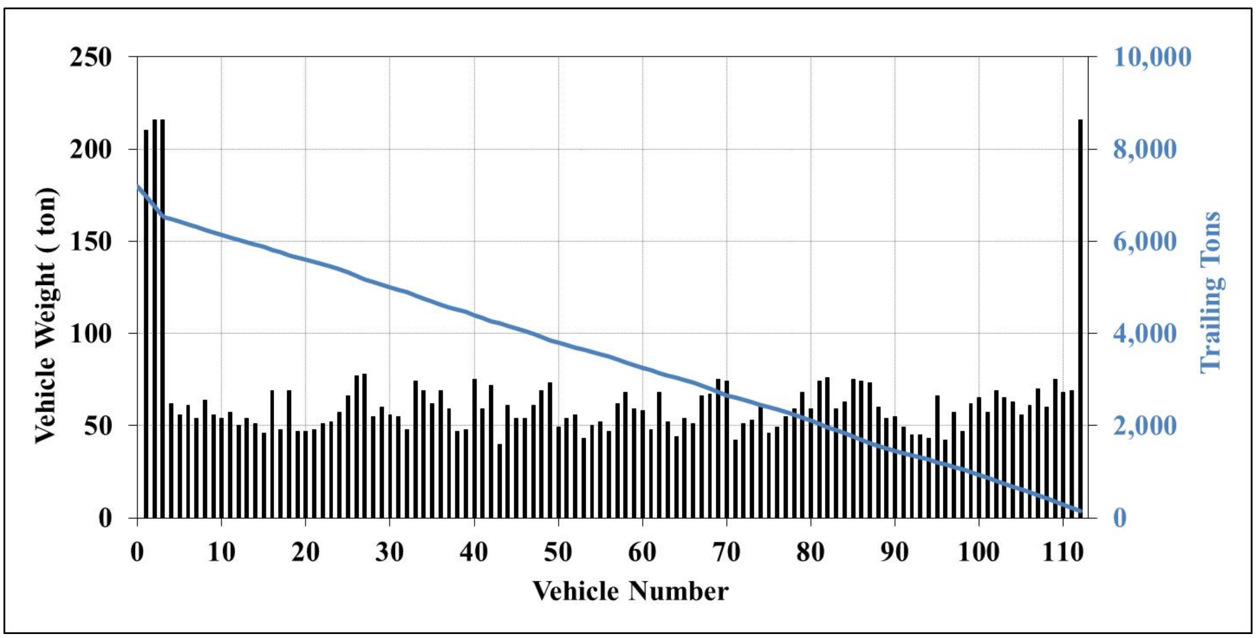


Figure 4.2-13. Eastbound Goodwell, OK train weight distribution.

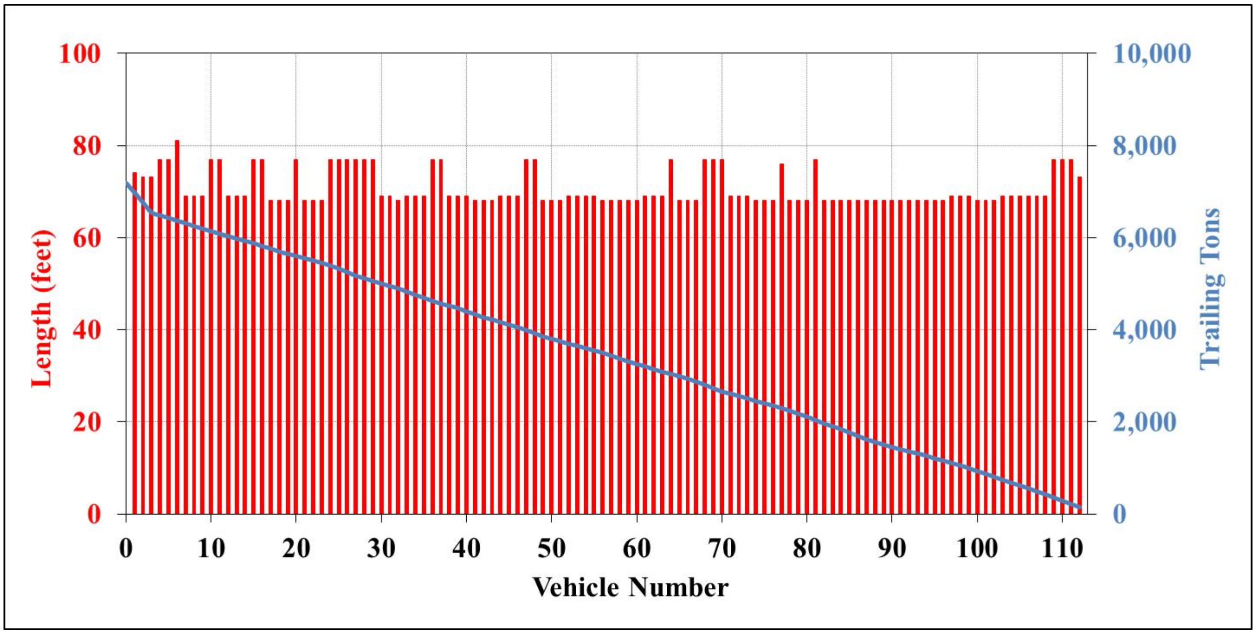


Figure 4.2-14. Eastbound Goodwell, OK train length distribution.

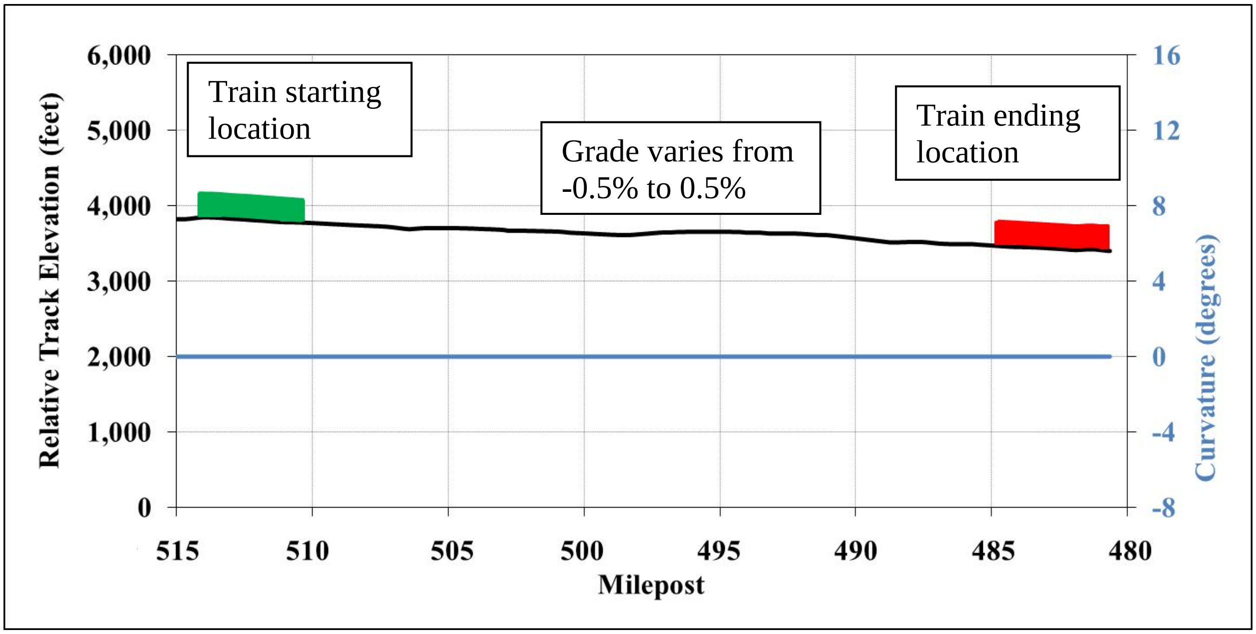


Figure 4.2-15. Eastbound Goodwell, OK track chart.

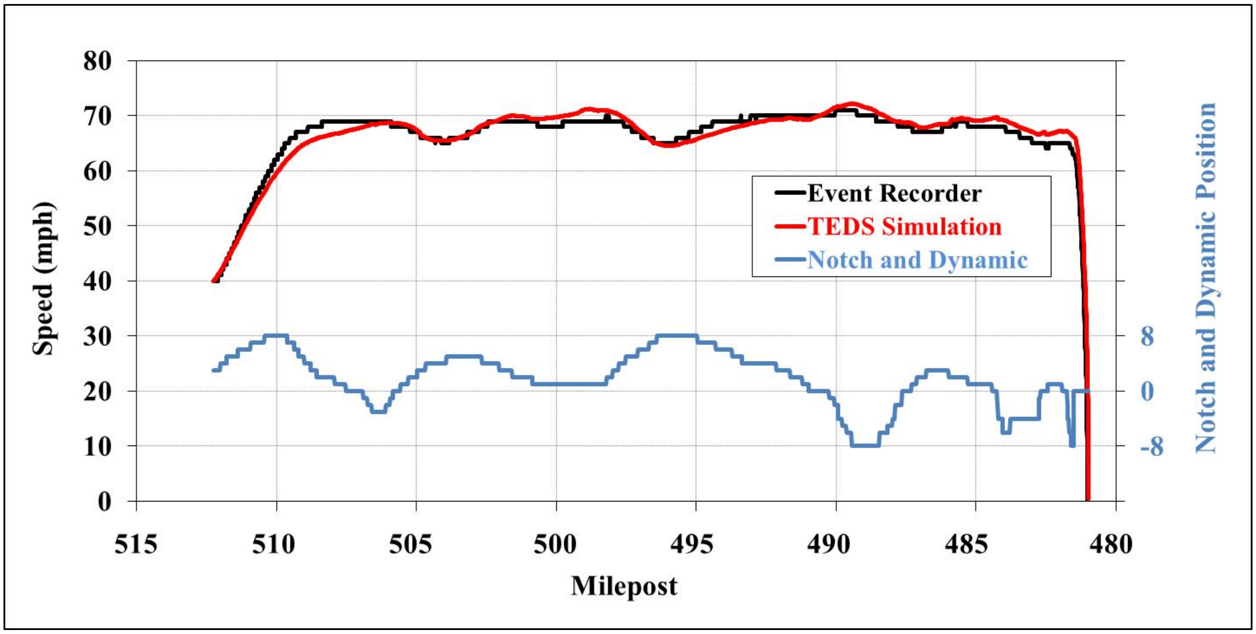


Figure 4.2-16. Eastbound Goodwell, OK train handling and speed comparison.

5. Detailed Coupler Force System Validation

The third major element of validation of TEDS is the coupler force model. The only measured revenue service data available for this purpose is from an ASME paper [5] and an AAR report [9]. We selected the cresting event from these documents because the large changes in coupler force can be compared with the predictions of the draft gear model, and the loaded stop event can be compared with the predictions of the speed and stopping distance model.

5.1 Unit Train Cresting Operation

For this validation process, published test data for a revenue service unit coal train was obtained from a paper presented at an October 1992 ASME Rail Technology Division (RTD) meeting and a report issued by the American Association of Railroads [5, 9]. A summary of the train in this revenue service test is provided in Table 5.1-1, while the weight and length distributions are shown in Figure 5.1-1 and Figure 5.1-2, respectively.

Table 5.1-1. Conventional unit train summary.

No. of Locomotives	Head-end	4
	Middle	2
	Remote/Rear	0
Total Horsepower		20,200
No. of Cars	Total	99
	Empty	2
	Loaded	97
Trailing Tons		13,958
Total Tons		15,061
Horsepower/Ton		1.34
Train Length (Including Locomotives) in feet		6,086

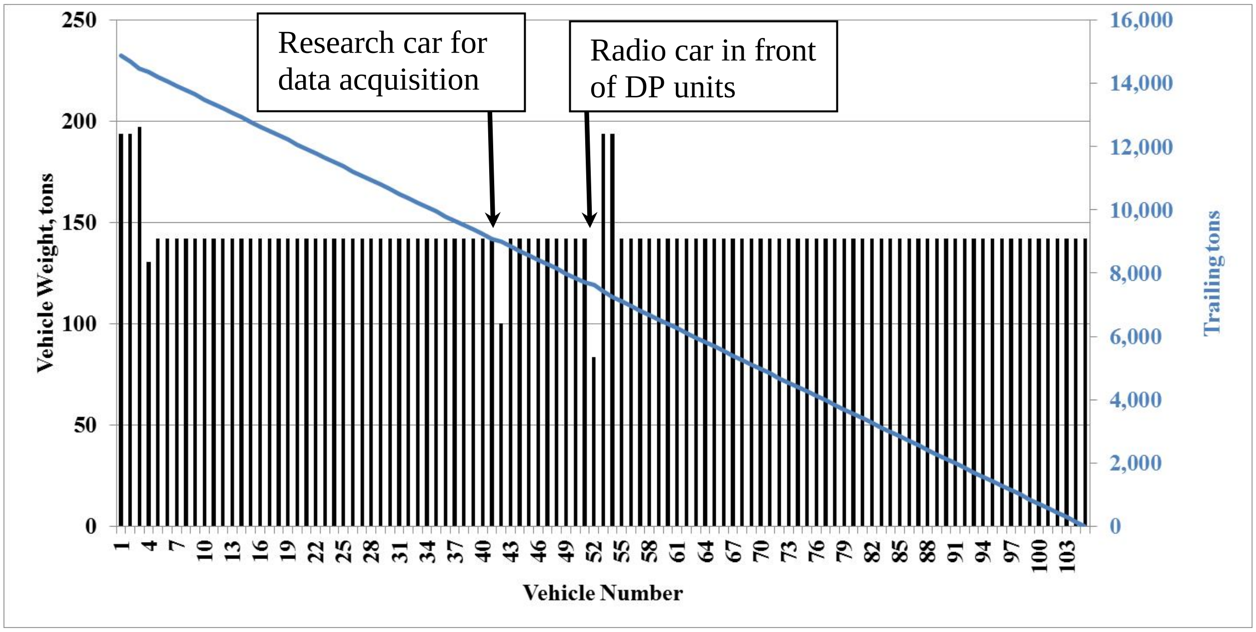


Figure 5.1-1. Conventional unit train weight distribution.

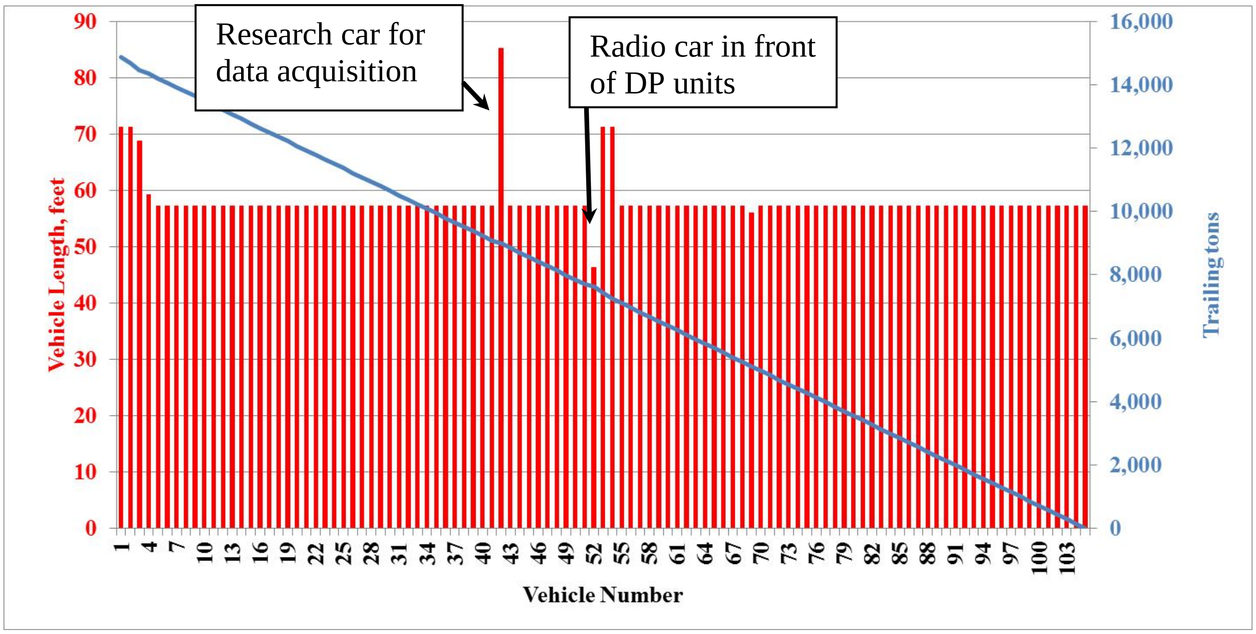


Figure 5.1-2. Conventional unit train length distribution.

Figure 5.1-3 shows the elevation profile, while Figure 5.1-4 compares the train speed predicted by TEDS and with the measured speed, together with the train handling for this scenario. The predicted speed matches the measured speed very well. Each of the throttle position changes are reflected in the speed at each of the knee points.

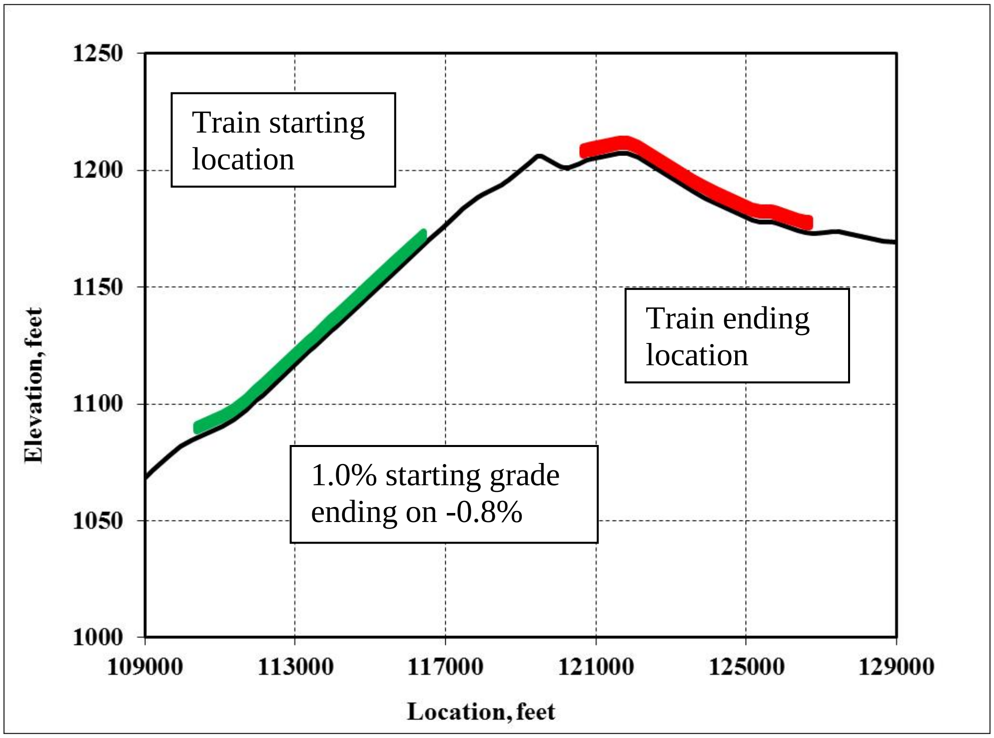


Figure 5.1-3. Cresting operation elevation profile.

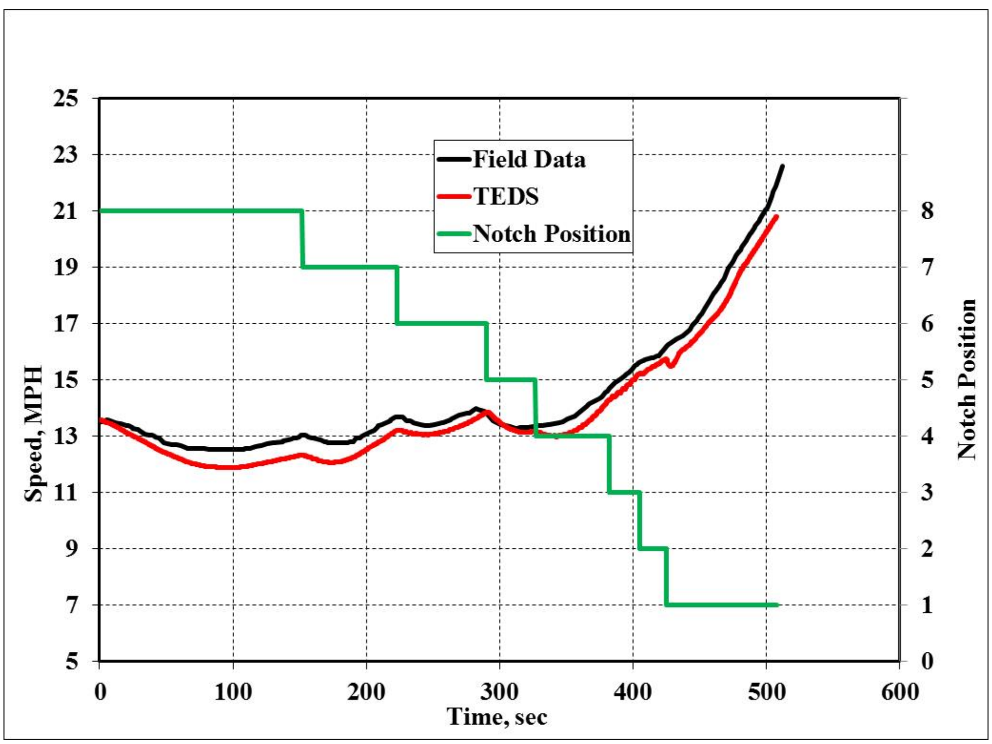


Figure 5.1-4. Comparison of predicted speed to measured speed for cresting operation.

The coupler force was measured and plotted for cars 1, 17, and 57 on the train. The comparison of the predicted coupler force to the measured coupler force is shown in Figure 5.1-5 through Figure 5.1-7. In all cases the predicted coupler force matches the measured coupler force well.

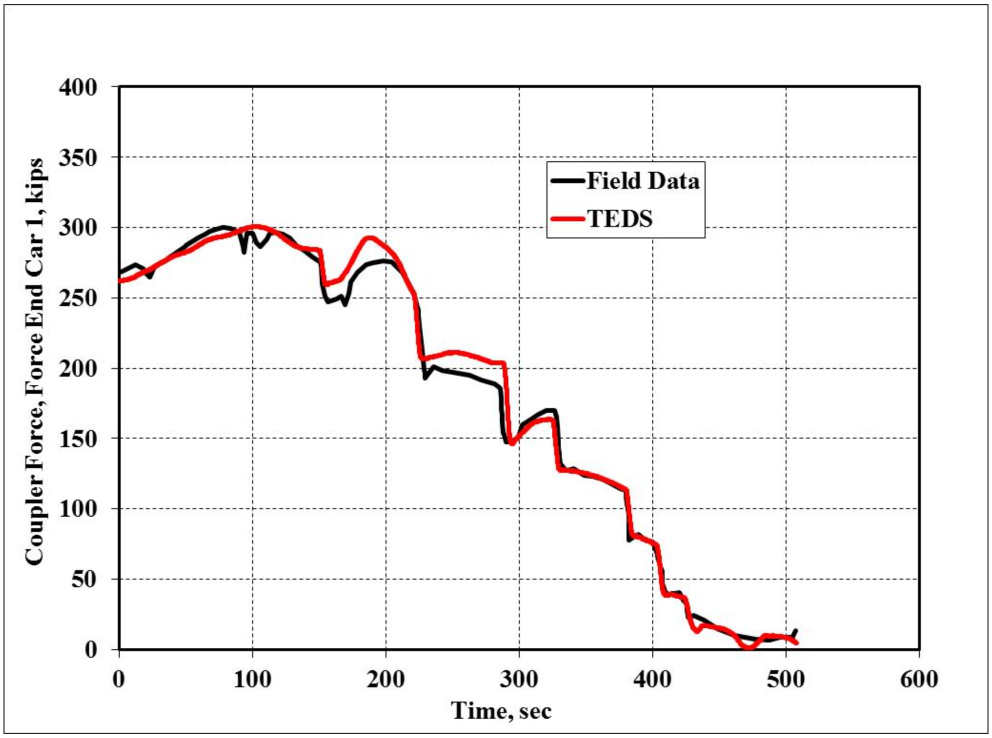


Figure 5.1-5. Comparison of predicted to measured coupler force on car 1 for the cresting operation.

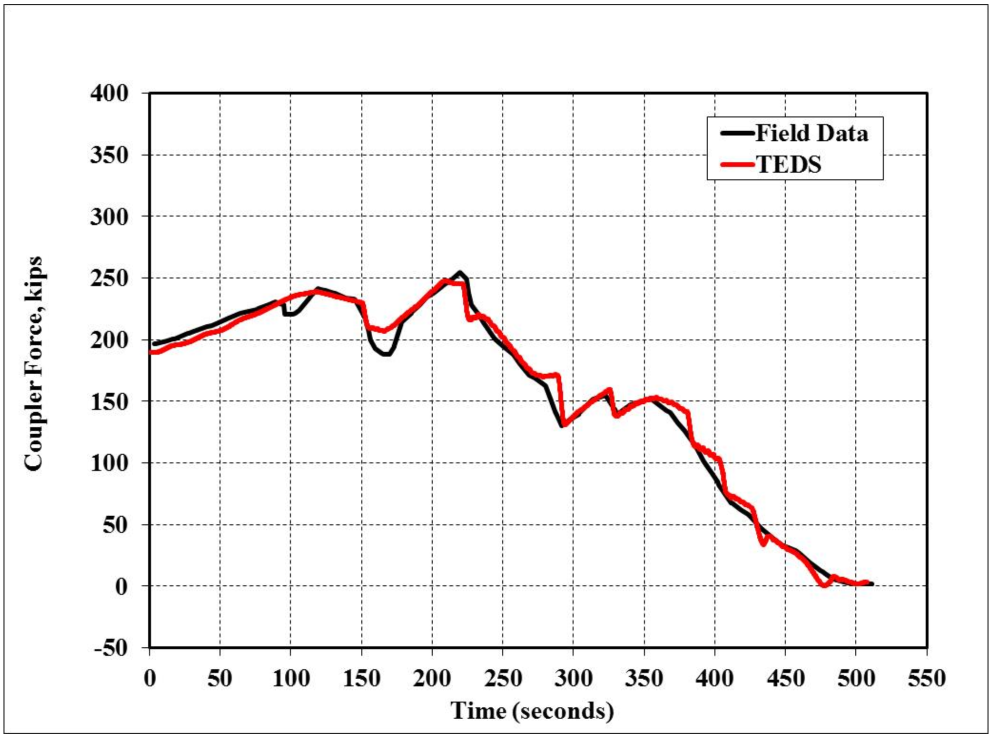


Figure 5.1-6. Comparison of predicted to measured coupler force on car 17 for the cresting operation.

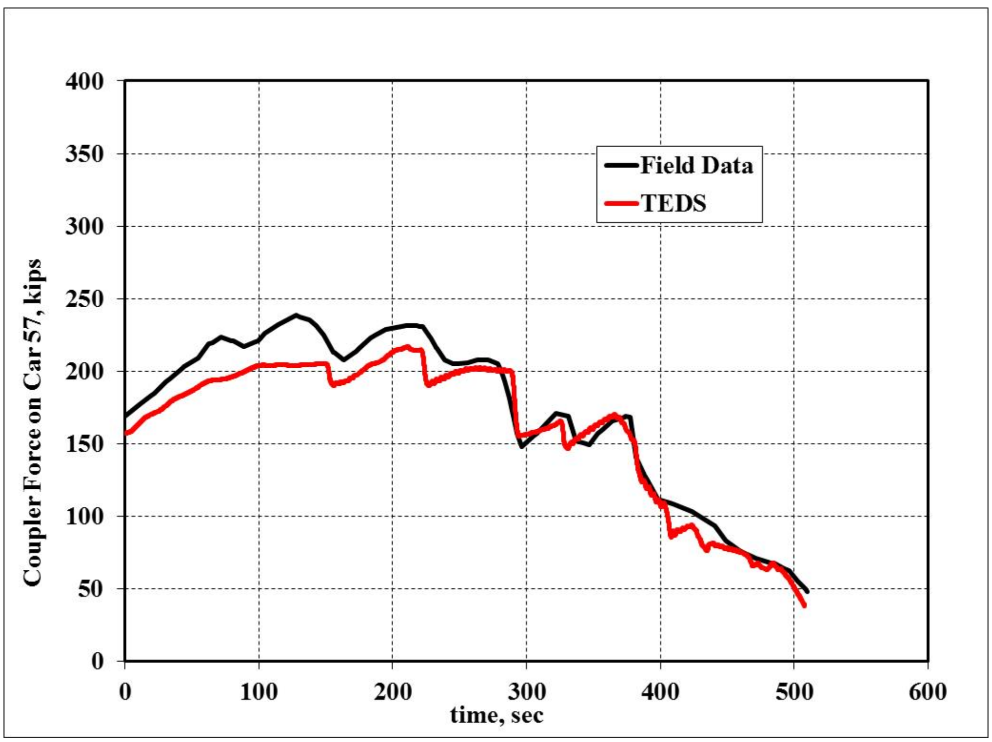


Figure 5.1-7. Comparison of predicted to measured coupler force on car 57 for the cresting operation.

5.2 Unit Coal Train Full Service Application Stop

The unit train's full service stop included the air brake system response discussed in Section 4.1. The track profile for this scenario is shown in Figure 5.2-1. The TEDS prediction of train speed is shown in Figure 5.2-2. The speed profile shows a good match, and the stopping location is within 15 feet, which is excellent. The increase in speed shown toward the end of the profile in both the test data and in the TEDS simulation is due to the release of the air brakes.

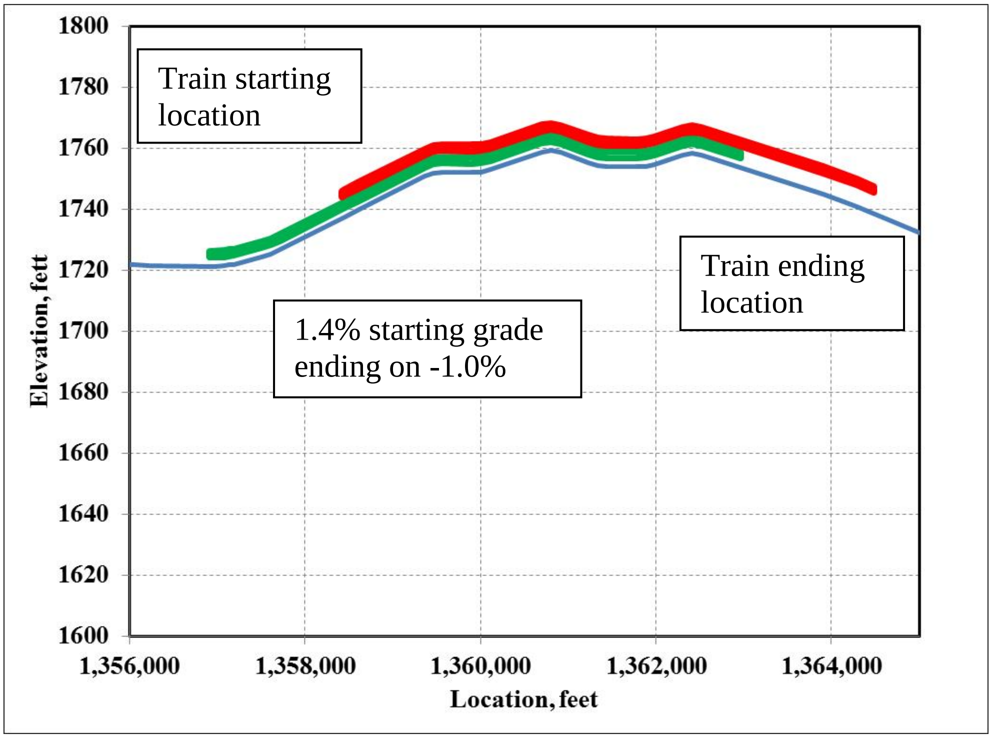


Figure 5.2-1. Full service application track profile.

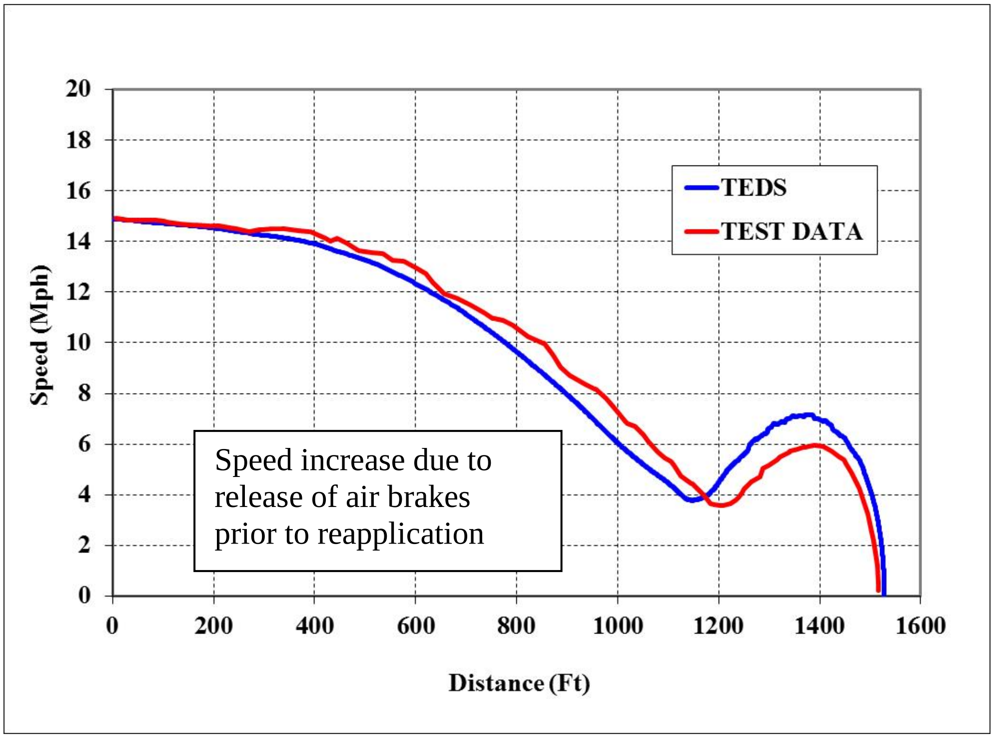


Figure 5.2-2. TEDS predicted speed compared to measured test data.

6. Conclusions

Validation criteria were developed and used to compare predictions made by TEDS at the component and system level with publicly available published laboratory and field data.

The air brake model predictions for the conventional automatic brakes as well the ECP brakes followed all of the test rack and test train trends well and matched the magnitudes well. The draft gear model predictions matched the impact data well, as well as the limited test train measured data available. TEDS predicted train speeds and stopping distance well. The model predicted a very good match of recorded train speed for relatively long distances.

Overall, the validation demonstrated that TEDS is a high fidelity model that realistically predicts longitudinal train behavior under a variety of operating conditions, including acceleration, braking, steady state running, operating over hilly terrain, and certain emergency conditions. Further, the effort demonstrated that TEDS' predictions are realistic for both gross train dynamics, measured by parameters such as position, velocity, and stopping distance, as well as, for inter-car dynamics, measured by parameters such as coupler forces.

7. References

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Abbreviations and Acronyms

AAR	American Association of Railroads
ASME	American Society of Mechanical Engineers
DP	Distributed Power
ECP	Electronically Controlled Pneumatic brakes
EOC	End-of-Car cushioning unit
FRA	Federal Railroad Administration
kips	kilo pounds
lbs	pounds
mph	miles per hour
NTSB	National Transportation Safety Board
TEDS	Train Energy and Dynamics Simulator
TOES	Train Operations and Energy Simulator