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Passenger Rail Train-to-Train Impact Test Volume I: Overview and Selected Results

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Washington, DC 20590

Rail Passenger Equipment Impact Tests

DOT/FRA/ORD-03/17.I

Final Report
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Tyrell, David

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U.S. Department of Transportation
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John A. Volpe National Transportation Systems Center
55 Broadway
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13. ABSTRACT (MAXIMUM 200 WORDS)

This report describes the results of the train-to-train impact test conducted at the Federal Railroad Administration's Transportation Technology Center in Pueblo, Colorado on January 31, 2002. In this test, a cab car-led train, initially moving at 30 mph and consisting of a cab car, three coach cars, and a trailing locomotive, collided with a standing locomotive-led train with two ballasted open-top hopper cars. The test included test dummies in the operator's seat of the impacted locomotive, and in the cab car and first coach car.

This test was the third of three tests intended to define the performance of current-design equipment in in-line collisions. The objective this test was to observe the interaction of the colliding equipment and to measure the environments experienced by the test dummies, as well as the responses of the test dummies.

During the train-to-train test, the cab car overrode the locomotive; the underframe of the cab car sustained approximately 20 feet of crush and the first three coupled connections sawtooth buckled. The short hood of the locomotive remained essentially intact, while there was approximately 12 inches of crush of the windshield center post. The test measurements of the response of the trains compare closely with predictions made with lumped-parameter models.

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PREFACE

This work was performed as part of the Equipment Safety Research Program sponsored by the Office of Research and Development of the Federal Railroad Administration (FRA). The authors would like to thank Tom Tsai, Program Manager, and Claire Orth, Division Chief, Equipment and Operating Practices Research Division, Office of Research and Development, for their support.

Gunars Spons, FRA's Resident Engineer at the Transportation Technology Center, directed and coordinated the activities of all the parties involved in the test. Barrie Brickle, Senior Engineer, Transportation Technology Center, Inc., implemented the equipment-related portions of the test. Caroline Van Ingen-Dunn, Senior Engineer, Simula Technologies, Inc., implemented the occupant-protection tests.

The authors would like to thank Edward Murphy, Chief Mechanical Officer, Southeastern Pennsylvania Transportation Authority (SEPTA), for arranging the donation of the cab car used in this test, as well as two other cars used in previous tests; David Elliot, Assistant Chief Mechanical Officer, Long Island Rail Road (LIRR) for arranging the donation of two coach cars used in this test, and two additional cars to be used in future tests; George Binns, Director of Safety, Amtrak, for arranging the donation of the two General Motors/ElectroMotive Division (GM/EMD) F40PH locomotives used in the test; Doug Karan, Senior Engineer, Amtrak for arranging the donation of the intercity passenger seats; Michael Lorenzen, Leader, Structural Analysis Group, for securing copies of the F40PH structural drawings; and Gordon Campbell, Senior Engineer, LDK Engineering, Inc., for securing copies of the SEPTA Silverliner I car and LIRR M1 car structural drawings from Bombardier, Inc. Thomas Peacock of the American Public Transportation Association was exceptionally effective in his efforts to coordinate the test with members of the passenger-rail transportation industry.

The authors would like to acknowledge the assistance of the National Highway Transportation Safety Administration, which provided six test dummies, and the Federal Aviation Administration, which provided four load cells.

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

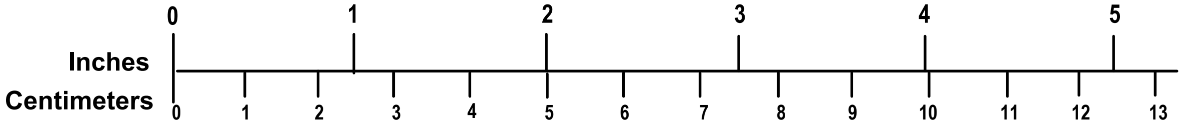
VOLUME (APPROXIMATE)

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 CONVERSION

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

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

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

This report describes the results of the train-to-train impact test conducted at the Federal Railroad Administration's Transportation Technology Center in Pueblo, Colorado on January 31, 2002. In this test, a cab car-led train, initially moving at 30 mph, collided with a standing locomotive-led train. The initially moving train included a cab car, three coach cars, and a trailing locomotive, while the initially standing train included a locomotive and two open-top hopper cars. The hopper cars were ballasted with earth such that the two trains weighed the same, approximately 635 kips each. The cars were instrumented with strain gauges, accelerometers, and string potentiometers, to measure the deformation of critical structural elements, the longitudinal, vertical, and lateral car body accelerations, and the displacements of the truck suspensions. The test included test dummies in the operator's seat of the impacted locomotive, in forward-facing conventional commuter passenger seats in the cab car and first coach car, and in intercity passenger seats modified with lap and shoulder belts in the first coach car.

This test was the third of three tests intended to define the performance of current-design equipment in in-line collisions. The first test consisted of a single passenger car impacting a fixed barrier, with the principal objective of measuring the force required to cause significant crush of the car and to observe the geometry of the crushed structure. The second test consisted of two-coupled passenger cars impacting a fixed barrier, with the principal incremental objective of measuring the interaction of the coupled cars, i.e., the kinematics of the coupling during the impact and the influence of the trailing car on the leading car's deceleration. The principal incremental objective of the train-train-test was to observe the interaction of the colliding equipment and to measure the environments experienced by the test dummies, as well as the responses of the test dummies.

During the train-to-train test, the cab car overrode the locomotive; the underframe of the cab car sustained approximately 22 feet of crush and the first three coupled connections sawtooth buckled. The short hood of the locomotive remained essentially intact, while there was approximately 12 inches of crush of the windshield center post. There was nearly no damage to the other equipment used in the test.

Preliminary analyses of the structural and occupant protection measurements have been completed. Analysis predictions of the crush and decelerations of the cars and locomotive compare closely with test measurements. The structural measurements are currently being used to refine simulation models. The occupant protection measurements are being used to evaluate the influence of the vertical and lateral accelerations on occupant response, by comparing them with previous sled test measurements. During the test, the cab car operator's compartment and the space for ten rows of seat was lost in the cab car, and life-threatening injury values were measured by the test dummies in the first coach car.

Preparations are underway for testing equipment with crash energy management system (CEM). Single car, two car, and train-to-train tests are planned.

1. INTRODUCTION

The approach taken by the Federal Railroad Administration's (FRA) Office of Research and Development in conducting research into rail equipment crashworthiness has been to review relevant accidents and identify options for design modifications. Analytic tools and testing techniques are used to evaluate the effectiveness of these options.

As part of this research, computer models have been developed and applied to determine the response of rail equipment in a range of collision scenarios [1, 2, 3, 4, 5, 6]. In-line and oblique train-to-train collisions, as well as grade crossing collisions and rollover events subsequent to derailment have been modeled. The responses of locomotives, cab cars, and coach cars in a range of collision scenarios have been simulated.

To assess the validity of the models, results of these analyses have been compared with accident data, and component test results [7]. While providing useful information and some assurance of the validity of the models, accident data and component and subscale testing all have limitations. There is uncertainty about the initial conditions of any accident — the speeds and locations of the two colliding objects are never precisely known. In addition, there is no information on the trajectories of the objects involved in the collision which lead to their resting places; this information must be inferred from the results of the accidents. The support and loading conditions in component tests can only approximate the actual conditions these components experienced during a collision.

Competing modes of crush (e.g., bending, bulk crushing, and material failure) cannot be consistently scaled for subscale testing [8]. Either one mode of crush must be chosen as the dominant mode and the other modes ignored, or it must be assumed that the simulation accurately scales the competing modes. Full-scale impact tests are necessary in order to know precisely the initial conditions, to measure the trajectories of the equipment during the impact, and to provide the appropriate support conditions for the structure that crushes during the impact, as well as to allow the competing modes of crush to appropriately contribute to the overall crush of the structure.

1.1 PLANNED TESTS

Two series of tests are planned, one based on a head-on collision scenario, in which a cab car-led train collides with a locomotive-led train, and the second based on a grade-crossing collision scenario, in which a cab car-led train collides with a tractor trailer carrying a coil of sheet steel.

Figure 1 shows a schematic representation of the in-line collision scenario. Examples of such collisions include the Prides Crossing, Massachusetts, collision between a commuter train and a freight train [9] and the Placentia, CA collision between a cab-car led commuter train and a locomotive-led freight train [10].

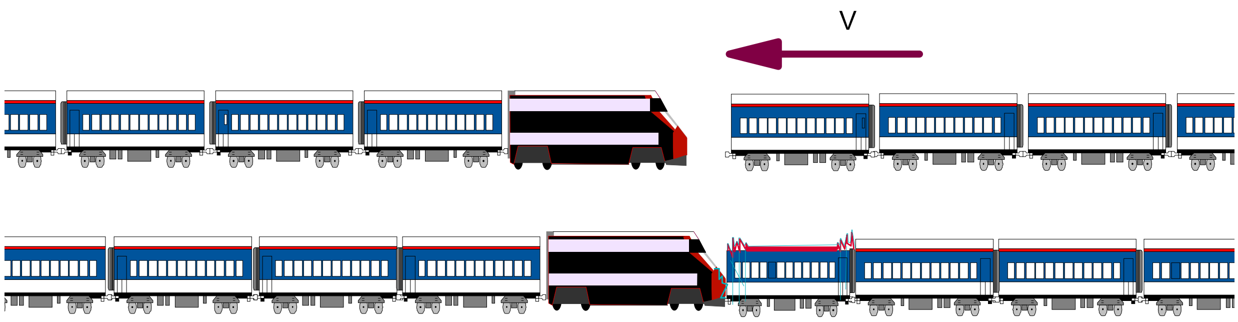


Figure 1. Schematic of In-Line Collision Scenario

Figure 2 shows a schematic representation of the grade-crossing collision scenario. Examples of such collisions include the Portage, Indiana collision between a cab-car led commuter train and a tractor-tandem trailer carrying coils of steel [11] and the Yardley, Pennsylvania collision between a cab-car-led commuter train and a tractor semi-trailer carrying coils of steel [12].

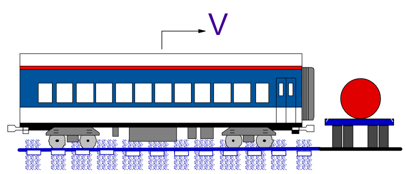


Figure 2. Schematic of Grade-Crossing Collision Scenario

The conditions and the sequence of the tests are listed in Table 1. The overall objective of these tests is to demonstrate the effectiveness of improved-crashworthiness equipment. The first series of four tests define the crashworthiness of conventional equipment in the in-line and grade-crossing collision scenarios. The performance of improved-crashworthiness equipment is to be measured in the second series of four tests. This arrangement of the tests allows comparison of the conventional-equipment performance with the performance of improved-crashworthiness equipment. The in-line collision tests are intended to measure the crashworthiness of a single car, then the interactions of two such cars when coupled, and finally the behavior of complete trains, including the interactions of the colliding cars. The grade-crossing collision tests are intended to measure the effectiveness of the car end structure in preventing intrusion during a grade-crossing collision.

Table 1. Planned Sequence of Full-Scale Passenger-Equipment Impact Tests

Test Conditions	Conventional-Design Equipment	Improved-Crashworthiness Design Equipment
Single-car impact with fixed barrier	Test 1 November 16, 1999	Test 6 Date TBD
Two-coupled-car impact with fixed barrier	Test 2 April 4, 2000	Test 7 Date TBD
Cab car-led train impact with locomotive-led train	Test 3 January 31, 2002	Test 8 Date TBD
Single-car impact with steel coil	Test 4 June 4, 2002	Test 5 June 7, 2002

To date, the first three in-line tests for existing-design equipment and the two grade-crossing tests have been conducted. Testing of improved crashworthiness design equipment, incorporating CEM structures, in the tests based on the in-line collision scenario is planned to start in the summer of 2003.

This report is organized as follows:

Section 1 (This): "Introduction" – generally describes the collision test program and the organization of this report.

Section 2: "Train-to-Train Test" – describes the train-to-train test conducted on January 31, 2002 and a summary of the results obtained.

Section 3: "Train-to-Train Test Measurements and Analysis Results" – presents specific information on measurements and modeling estimates for such as energy, maximum crush values, and time histories for certain parameters.

Section 4: "Discussion" – summarizes the report findings and describes the next steps in the testing program.

Appendix A: "Test Requirements" – provides a summary of instrumentation details and why specific instrumentation was implemented.

Appendix B: ""Post Processing of Data" – describes the procedures used to filter and compile the data collected (ex. accelerometers).

Appendix C: "Models and Predictions" – describes the single-dimensional and three-dimensional models developed to accurately predict the reaction of passenger cars in a crash.

1.2 SUMMARY DESCRIPTION OF IN-LINE TESTS

The in-line tests were organized as tests of increasing complexity, both in terms of the tests themselves and in terms of the information gathered. The first test was of a single car, the second test was of two coupled cars, and the third test was of two colliding trains [13]. Figure 3 shows schematics of the single-car test [14, 15, 16], the two-car test [17, 18, 19], and the train-to-train test, in which a cab-car-led train impacts a standing locomotive-led train. The objectives of the single-car test were to observe the failure modes of the major structural components, to measure the gross motions of the car, and to measure the force/crush characteristic. The two-car test had the added objective of measuring the interactions between the coupled cars. The train-to-train test further added the objective of measuring the interactions between the colliding locomotive and cab-car. All of the tests also included experiments to measure the response of test dummies in selected interior configurations.

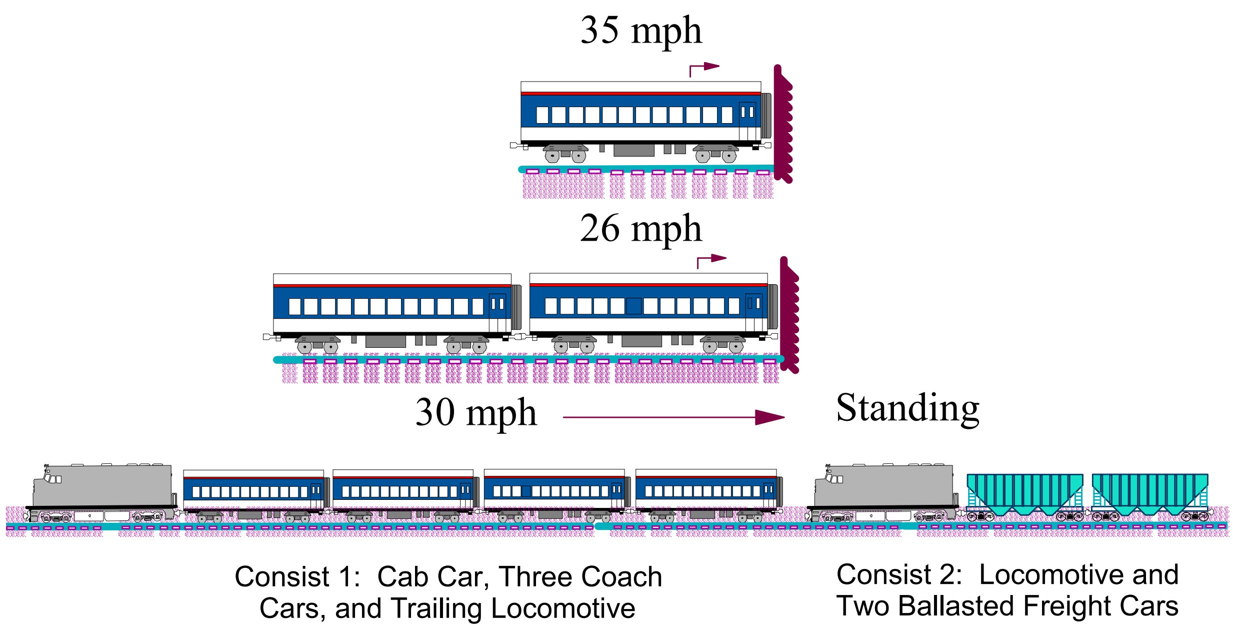
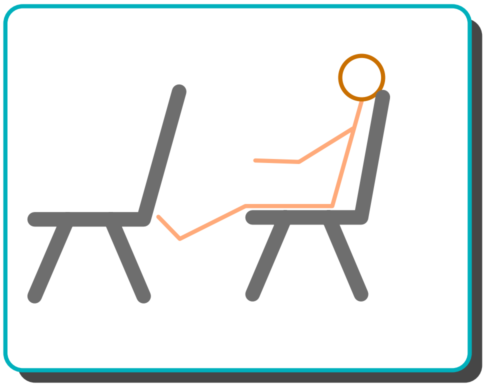
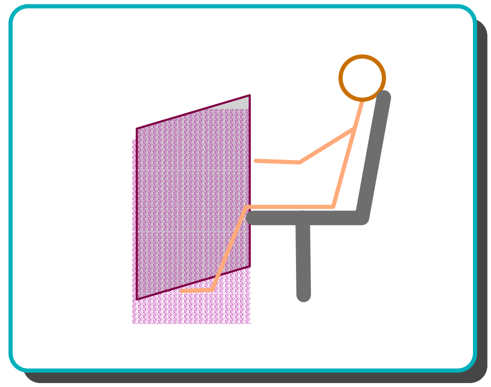


Figure 3. Schematic of Single Car, Two Car, and Train-to-Train Tests

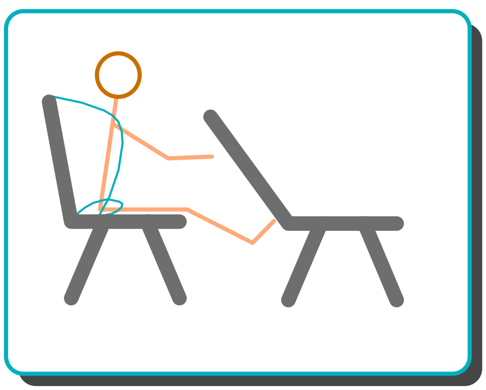
Figure 4 shows schematics of the occupant-protection experiments included as part of the in-line car tests. In the single-car and the leading car in the two-car tests, forward facing commuter passenger seats, rear-facing commuter passenger seats, and forward facing inter-city passenger seats with lap and shoulder belts were tested. Also in the trailing car of the two-car test, the forward-facing commuter passenger seats were additionally tested. In the train-to-train test, tests were conducted using three types of seats. Forward facing commuter passenger seats were tested in the cab car in the train-to-train test, as well as in the first coach car. Inter-city passenger seats with lap and shoulder belts were tested in the first coach car. Finally, a pedestal type locomotive operator seat was tested in the impacted locomotive. Test dummies were used in all the occupant protection experiments. The principal objective of these tests is to measure the responses of test dummies in several interior configurations. Additionally, the train-to-train test will use the response measurements to evaluate the potential for occupant injury.



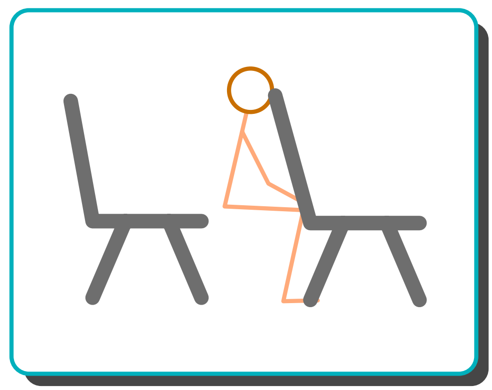
Rear Facing Occupant



Locomotive Operator



Occupant with Lap Belt and Shoulder Harness



Forward Facing Occupant

Figure 4. Schematic of Forward Facing Commuter Passenger Seat, Rear Facing Commuter Passenger Seat, Forward Facing Inter-City Passenger Seat, and Locomotive Operator's Interior Experiments

Table 2 summarizes the critical measurements for each of the three in-line tests. While the overall objective of these tests is to demonstrate the effectiveness of improved-crashworthiness equipment, the test data are also being used for comparison with analyses and modeling results. The measurements will be used to refine these analyses' approaches and models, and to ensure that the factors influencing the response of the equipment and test dummies are taken into account. The table lists the measurements that are critical to ensuring the appropriate modeling and analysis of the equipment and test dummies.

Table 2. Test Descriptions and Critical Measurements

Test Description	Critical Measurement
Single-Car Test	• Dynamic crush force • Occupant volume deceleration • Effectiveness of compartmentalization, rear-facing seats, and seats with lap and shoulder belts
Two-Car Test	• "Sawtooth" lateral buckling of coupled cars • Influence of trailing car on maximum occupant volume deceleration • Effectiveness of compartmentalization, rear-facing seats, and seats with lap and shoulder belts
Train-to-Train Test	• Override of colliding cars • Lateral buckling of coupled cars • Effectiveness of compartmentalization, and seats with lap and shoulder belts • Measurement of operator secondary-collision environment and test dummy response

1.2.1 Single-Car Test

Figure 5 shows the force/crush characteristics developed from measurements made during impact tests of a single passenger car into a fixed barrier [14]. This curve has high initial peak load followed by significantly lower loads, which are approximately constant, for continued crush.

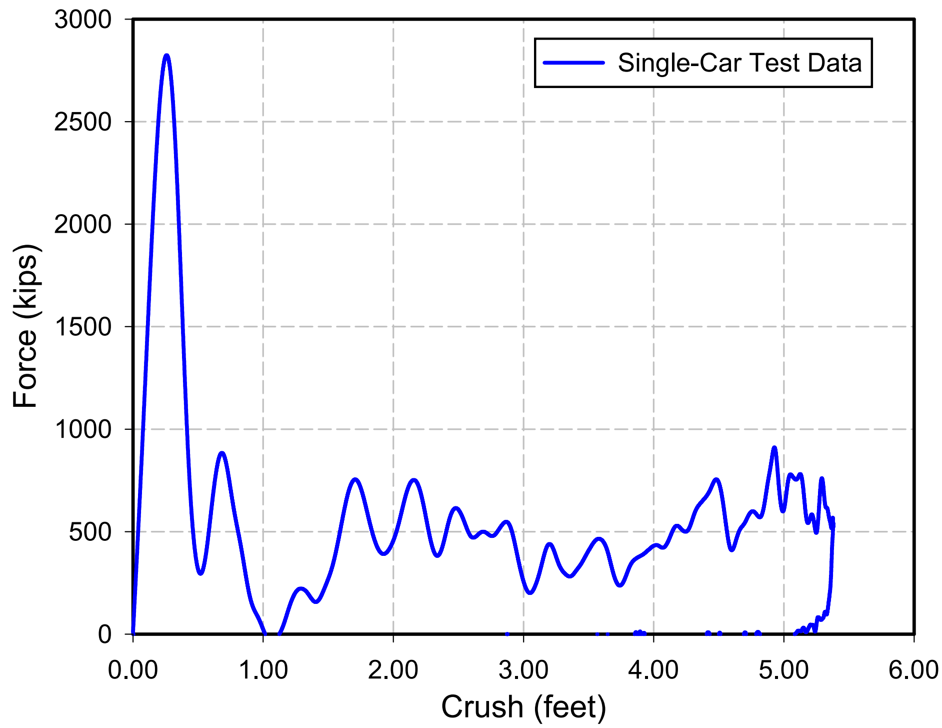


Figure 5. Force/Crush Characteristic Developed from Single-Car Test Measurements

One implication of the force/crush characteristic shown in Figure 5 is that the crush will be focused on the colliding cars. If two trains, which are made up of cars with the crush characteristics shown in Figure 5, collide, at best only the two colliding cars will crush. Indeed, only one of the colliding cars may crush if the other colliding car has a marginally greater peak crush load. This is principally owing to the inability of a colliding car to push back with sufficient force to crush the car behind it. In the test of two coupled cars impacting with a fixed barrier [17, 20, 21], the lead car sustained significant structural damage – its length was reduced by nearly two meters – while the front end of the trailing car sustained only minor scarring due to the direct contact with the trailing end of the lead car. The most force the car ahead can exert is the lower crush load, while the car behind can apply up to the peak load. There is often little crush damage to the trailing cars in train collisions of typical U.S. passenger rail equipment.

1.2.2 Two-Car Test

During the two-car test, the cars remained coupled, but buckled in a saw-tooth mode. This buckling is due to the linkage behavior of the couplers used on North American passenger equipment. These couplers form a rigid link between cars; when there is a high longitudinal load present, with only a small perturbation, the link formed by the couplers pushes laterally on the ends of the cars. As a result, the ends of the cars are laterally offset from each other when they contact. The maximum lateral displacement between the cars during the collision was approximately 30 inches. The final lateral displacement was 15 inches. The left track buckled under the lateral load from the front truck of the trailing car, allowing the right wheels of the front truck of the trailing car to drop. Figure 6 shows the coupled connection between the two cars at their final lateral displacement.

Figure 6. Sawtooth Lateral Buckling of Coupled Cars Observed in Two-Car Test

Once the cars are misaligned, the high longitudinal force acting on one car exerts a significant lateral component on an adjacent car. Consequently, the train will continue to buckle out into a relatively large amplitude zigzag pattern if there is sufficient energy from the collision. Depending on the severity, this mode may progress until the cars have side-to-side impacts. Sawtooth buckling, zigzag buckling, and side-to-side impacts due to zigzag buckling have been observed in accidents [9, 22, 23]. The progression of the cars from in-line, to the sawtooth lateral buckling pattern, then to the zigzag pattern has been simulated [4] with computational models.

1.2.3 CEM TEST

For the train-to-train test of crash energy management equipment it is anticipated that the car crush will be distributed among the ends of the all the cars. As a result, there should be no intrusion into the occupant volume. In the train-to-train test of conventional equipment, the crush was focused on the leading end of the leading car, resulting in loss of occupant volume for the first ten rows of passenger seats.   For the CEM equipment, there is predicted no loss of occupant volume for the passengers. There is potentially loss of volume for the operator; however, means of protecting the operator, such as an operator's cage that gets pushed back into a utility closet in the event of a collision, are being investigated.

The occupant environment during the train-to-train test of the CEM equipment is expected to have slightly higher longitudinal decelerations, but lower vertical and lateral accelerations than during the train-to-train test of the conventional equipment. Overall, the occupant environments in the two tests are expected to be approximately equivalent, in terms of the likelihood of occupant injury.

Fullscale tests based on a grade-crossing collision with a heavy rigid object have also been implemented. These tests were used to evaluate the end structure of the cab car above the floor. Two such tests were conducted, one of a conventional cab car and another of a cab car with the end structure vertical elements – the corner posts and collision posts – tightly tied together with transverse elements. These tests were performed on June 4 and June 7, 2002.

2. TRAIN-TO-TRAIN IMPACT TEST

During the train-to-train impact test, the leading cab car overrode the stationary locomotive and sustained approximately 20 feet of crush of the underframe. In addition, the cab car started to deflect to its left as it overrode the locomotive. There was relatively little damage to the stationary locomotive, other than a modest amount of crush of the windshield. A portion of the cab car roof penetrated the locomotive through the windshield on the conductor's side. There was essentially no damage to the three coach cars and locomotive trailing the impacted cab car, or to the two ballasted freight cars trailing the impacted locomotive. Figure 7 shows the interaction of the colliding cab car and locomotive in a series of frames taken from high-speed video recorded during the test.

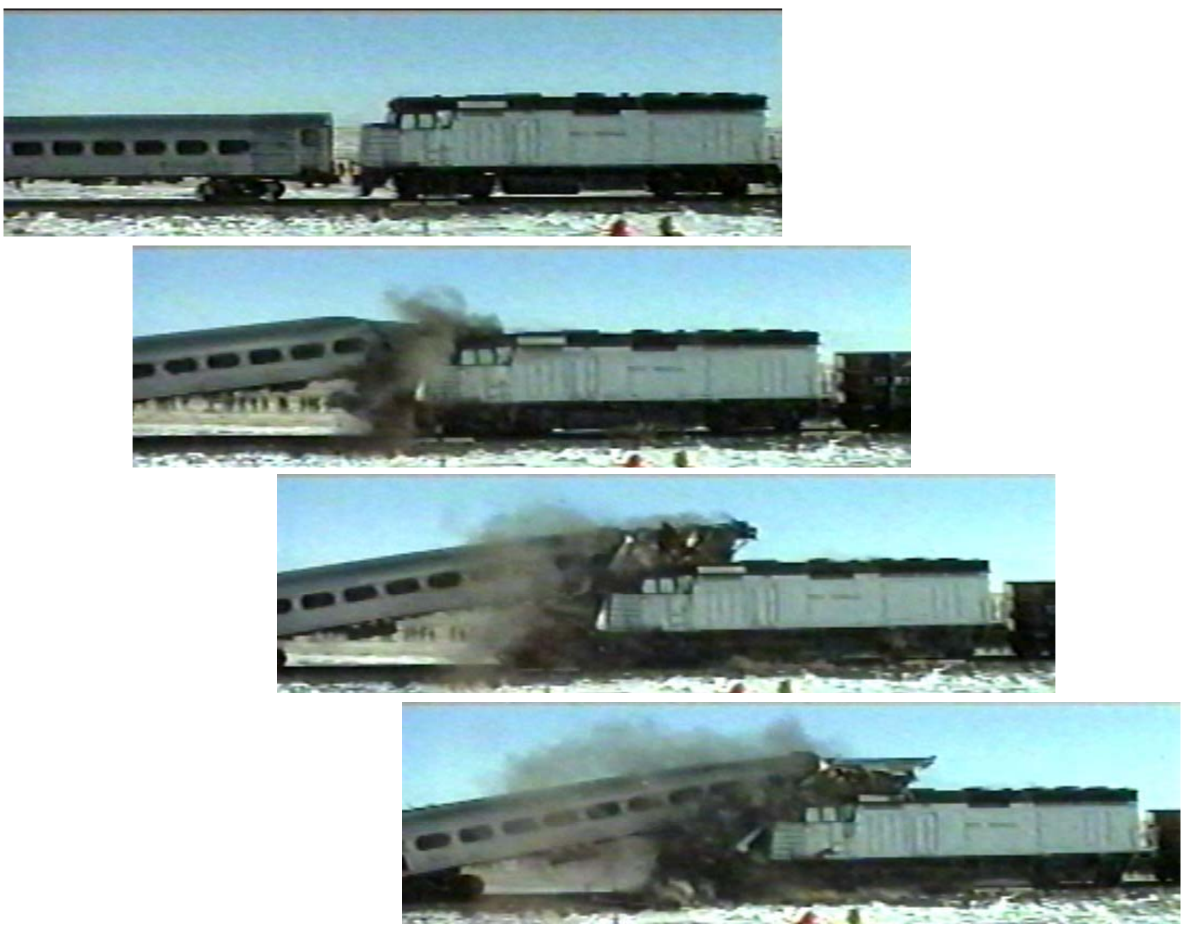


Figure 7. Override of Locomotive by Cab Car, Observed in Train-to-Train Test

Override during the train-to-train test was initiated by the failure mode of the underframe of the cab car, i.e., the cab car underframe essentially formed a ramp as it crushed. Such behavior was also observed during the single car and two car tests, where the end of the car was seen to rise approximately 6 inches during both tests. In the single car and two car tests, the end frame of the cab car remained in a fixed position against the wall, while the deformations of the underframe cause the end of the car immediately behind it to rise. Override continued in the train-to-train test due to the vertical offset of the longitudinal forces acting on the impacting end and the trailing end of the cab car. The impacting end rose vertically with the initial deformation of the cab car, while the trailing end remained near its initial height. The offset in longitudinal loads at each end of the cab car caused a pitching moment allowing the cab car to continue climbing the locomotive.

The initiation of lateral deflection was caused by the interaction of the couplers of the cab car and locomotive. The couplers by-passed each other on impact, forming a small laterally oriented ramp. The lateral displacement of the end of the cab car continued to grow during the impact, due to the lateral offset in the longitudinal forces acting at each end of the cab car.

Damage was focused on the cab car due to its inability to develop sufficient force to cause any of the trailing equipment to crush and to the locomotive being at least marginally stronger than the cab car. Shortly after the initial impact, before there was significant vertical offset between the cab car and the locomotive, the cab car was sufficient crushed to have passed its peak force, as shown in Figure 5. Once it had been crushed past its peak, the cab car was unable to exert sufficient force to cause significant damage to the trailing equipment or to the locomotive.

2.1 SUMMARY OF TEST REQUIREMENTS AND IMPLIMENTATION

In the train-to-train test, a cab car-led train, initially moving at 30 mph, collided with a standing locomotive-led train. The impact took place on level tangent track. The hand brake was set on the standing train; the brakes were released on the initially moving train. The cab car –led train included a cab car, three coach cars, and a trailing locomotive, while the locomotive-led train included a locomotive and two open-top hopper cars. The hopper cars were ballasted with earth such that the two trains weighed the same, approximately 635 kips each.

The test speed was chosen because it would cause substantial damage to conventional equipment, with resulting loss of occupant volume, yet with equipment incorporating an alternative crashworthiness strategy, the test conditions would be survivable. Simulations have shown that all the passengers can be protected by cars that incorporate crush zones in the ends in a train-to-train collision at 30 mph, for trains weighing 635 kips [24]. These crush zones are intended to crush in a controlled manner, distributing the crush among the cars of a train during an impact. Controlling the structural crushing and limiting it to the ends of the cars allows the occupant volumes to be preserved.

The cars were instrumented with strain gauges, accelerometers, and string potentiometers, to measure the deformation of critical structural elements, the longitudinal, vertical, and lateral car body accelerations, and the displacements of the truck suspensions. Approximately 200 channels of data were collected from the instrumentation on the cars.

The test included test dummies in the operator's seat of the impacted locomotive, in forward-facing conventional commuter passenger seats in the cab car and first coach car, and in intercity passenger seats modified with lap and shoulder belts in the first coach car. Approximately 100 channels of data were collected from all the test dummies.

2.2 MAKEUP OF TRAINS

The makeups of the trains were chosen to approximate trains that are used in push-pull commuter service, such as by the MBTA in Boston, VRE and MARC in Washington, NJT in New York and northern New Jersey, and Metra in Chicago. For such service, the cab car leads the train heading into the city, and the locomotive leads heading away from the city. Ballasted freight cars were chosen to trail the locomotive-led consist because the train weight was predicted to have the greatest influence on the results of the test; the number and type of cars was expected to have relatively little influence. Accordingly, a passenger locomotive and two freight cars were chosen to approximate a commuter train.

The cab car-led train was made up of a Budd Pioneer cab car, two Budd M1 cars, the T7 track geometry-measuring car, built by St. Louis Car, and a GM/EMD F40PH. The locomotive-led train was made up of a GM/EMD F40PH, and two ballasted open-top hopper cars. It had been originally planned to use four M1 cars in the initially moving consist, and not use the T7 car. T7 was substituted for two M1 cars because of difficulties in shipping the M1 cars from Long Island Railroad to TTC. As used in the test, the T7 car weighs nearly as much as two M1 cars. Figure 8 shows the initially moving cab car-led train just prior to the test.

Figure 8. Cab Car-Led Consist from Train-to-Train Test, Prior to Test

The end structure of the cab car was modified to comply with standards in place prior to 1999. A new end structure, consisting of corner posts, collision posts, an end beam and an anti-telescoping plate was fabricated and attached to the draft sill and roof plates. The design of the end structure was developed as part of the fullscale test program. (A report describing the design in detail is currently being written.) A photograph of the end structure is shown in Figure 9. The front skin was attached to the end structure prior to the test.

Figure 9. Modified Cab Car End Frame

The end structure of the locomotive was modified to comply with the current Association of American Railroad (AAR) S-580 Standard. The collision posts and front sheet of the short hood were replaced. The locomotive structural design was adapted from the design for locomotives supplied to the Metra commuter railroad provided by GM/EMD. The new front sheet did not include details such as cutouts for lights. Figure 10 shows the locomotive on the test track shortly before the test, along with the two ballasted open-top hopper cars.

Figure 10. Locomotive-Led Consist from Train-to-Train Test, Prior to Test

2.3 TEST RESULTS

The principal results of the train-to-train test include the crush of the equipment – the loss of occupant volume and the mode of deformation – and the interaction of the colliding equipment. During the test, the cab car underframe was crushed by approximately 22 feet, there was a modest amount of crush of the locomotive short hood and window structures, and there was only minor denting sustained by some of the remaining equipment. During the test, the cab car overrode the locomotive.

The duration of the test, from initial impact until both trains stopped, was approximately 8 seconds. Immediately after the initial impact, the cab car led train began to slow down, while the locomotive-led train began to move. After approximately 0.2 second and 18 feet of crush of the cab car underframe, the cab car started to override the short hood of the locomotive; the cab car then briefly impacted the window structure of the locomotive at about 0.6 second, crushing the underframe by an additional 2 feet, and finally rode up onto the roof of the locomotive cab after about 0.7 second. About 2 seconds after initial impact, both trains were moving at the same speed – approximately 15 mph. Subsequently, the cab car led train began to slow down at a greater rate than the locomotive-led train, and the cab car fell off the locomotive and the trains separated approximately 6.5 seconds after initial contact. Eventually, both trains came to a stop approximately 8 seconds after the initial impact. Figure 11 shows the cab car at approximately 0.75 second, the time of maximum override.

Figure 11. Frame Showing Cab Car at Maximum Override of Locomotive

Figure 12 is a sketch showing the positions of the cars after the test. The cab car sustained most of the damage during the test, while the locomotive received a relatively minor amount of damage. The first coach car behind the cab car sustained some damage to one of its collision posts on the end coupled to the cab car. This damage was due to the sawtooth buckling of the cab car and the first coach car. There was little, if any, damage to the other cars. Sawtooth buckling occurred at the connection between the cab car and the first coach, the first and second coach, and the second and third coach. The connection between the third coach and the trailing locomotive remained inline. The connections between the freight cars and between the leading freight car and the impacted locomotive all remained inline. While the lateral displacement of the lead end of the cab car was initiated during the impact, most of the lateral displacement occurred when the cab car and impacted locomotive separated.

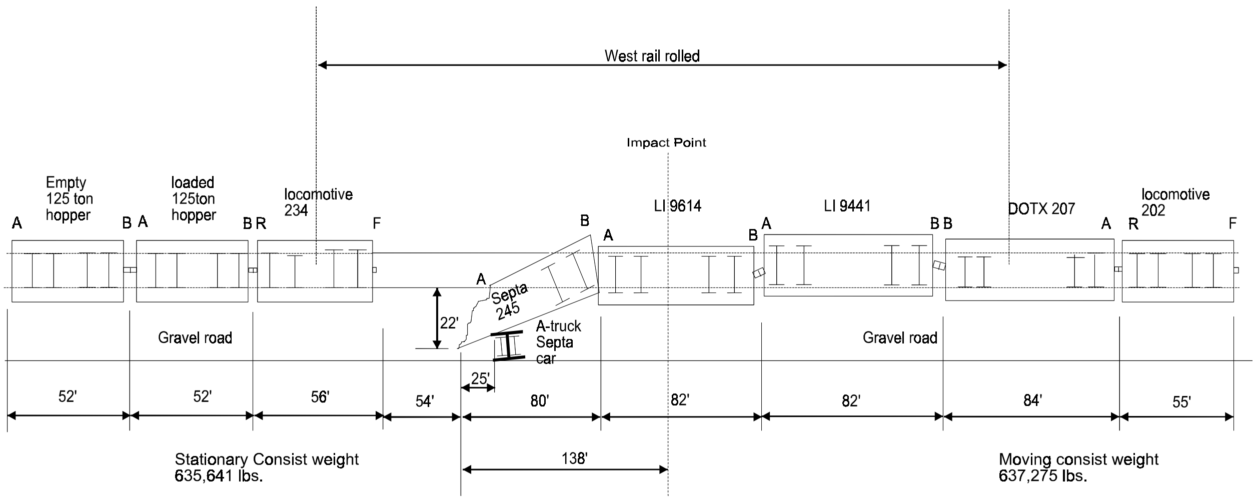


Figure 12. Sketch of Car Positions After Test

After the impact, there was approximately 22 feet of crush of the underframe and right sidewall of the cab car. Most of the roof and the left side wall of the cab car remained. The end frame of the car was pushed underneath, and ended up near the center of the car. The lead truck, separated from the cab car during the impact, was beside the remaining left sidewall at the crushed end of the cab car. The coupler and draft gear from the lead end of the cab car ended up underneath the lead axle of the lead truck of the first coach car. Figure 13 shows the cab car led consist immediately after the test.

Figure 13. Cab Car-Led Consist from Train-to-Train Test, After Test

During the test, the space for the operator's seat was lost, and the space for one half-row and approximately ten rows of passenger seats were lost. In total, seating for approximately 47 passengers were crushed during the test. Figure 14 shows an inside view of the crushed end of the cab car. The floor is pushed upward, owing to the end crush of the cab car; interior wall and roof panels have broken loose and intruded into the occupant space. Seats are presumed lost in the area where the floor is pushed up and the roof is coming down.

Figure 14. Interior of Cab Car, Looking Toward Crushed End-Led Consist from Train-to-Train Test, After Test

The impacted locomotive sustained a relatively small amount of damage. The coupler was pushed to the left and the left side and bottom of the bellmouth were broken. The short skirt on the underside of the anti-climber was dented on the right side, although the anti-climber itself remained essentially intact. There were a number of small dents in the front face of the short hood, especially near the top-center. The center pillar of the windshield was pushed back, and the conductor's side window was pushed into the operator's cab. The operator's side window remained partially in its frame. Both windows were crazed: each remained as a single sheet, but with substantial amounts of spall. The roof was dented above the center pillar of the windshield. Figure 15 shows the short hood end of the impacted locomotive after the test.

Figure 15. Impacted Locomotive, After Test

2.4 INTERIOR EXPERIMENTS

Interior experiments have been included in the in-line full-scale tests in order to observe the motions (kinematics) of the test dummies under collisions conditions and to measure the forces and decelerations imparted to the dummies. Four occupant protection experiments were included as part of the train-to-train test. Each of these experiments included instrumented test dummies to measure values for comparison with injury criteria and load cells to measure the loads imparted to the seats during the test. Each occupant protection experiment also included two high-speed film cameras. The four occupant protection experiments were:

- Test dummy in the operator's chair of the initially standing, impacted locomotive
- Test dummies unrestrained in forward facing rows of commuter passenger seats in the cab car
- Test dummies unrestrained in forward facing rows of commuter passenger seats in the first coach car
- Test dummies restrained by lap and shoulder belts in forward facing inter-city passenger seats in the first coach car.

Figure 16 shows the locations of the interior experiments inside the locomotive, cab car, and first coach car.

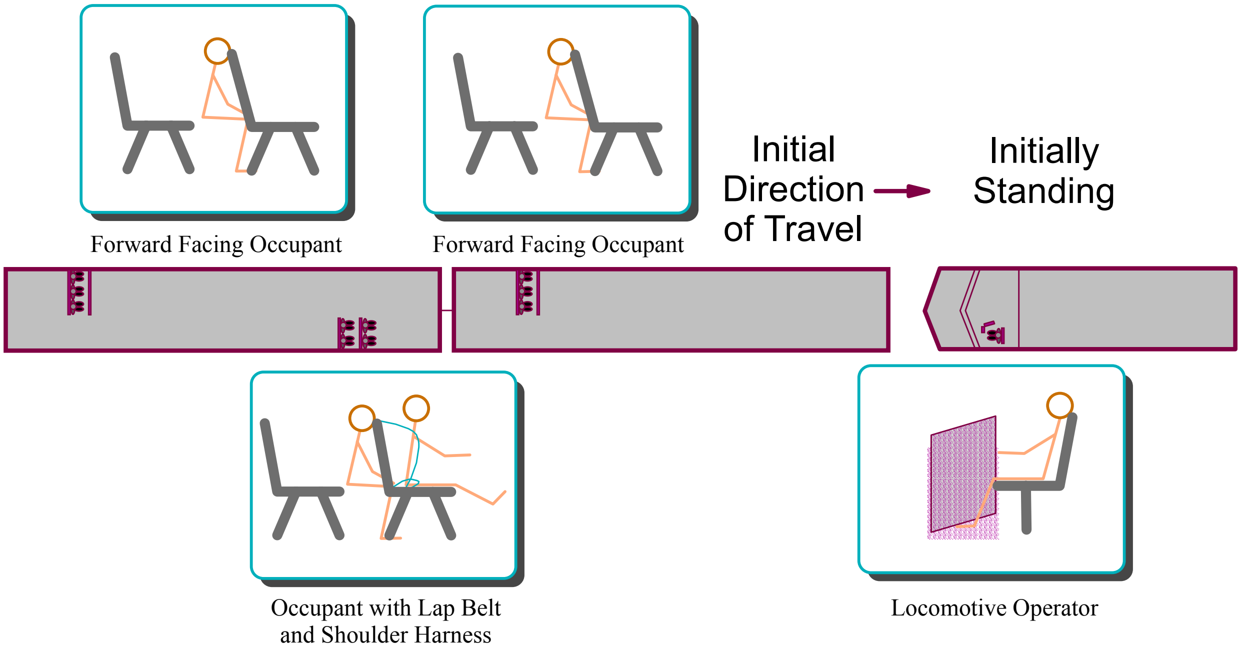


Figure 16. Locations of Interior Experiments

The injury criteria values computed from the test measurements all remained below NHTSA threshold values.

Figure 17 shows the interior experiment in the impacted locomotive, before and after the test. This experiment includes a Hybrid III test dummy of 95th percentile male stature. During the test the dummy moved forward relative to the control stand, and impacted a portion of the control stand. None of the NHSTA injury criteria threshold values was exceeded for this dummy. A portion of the roof of the cab car intruded into the cab during test, through the forward window on the conductor’s side of the cab.

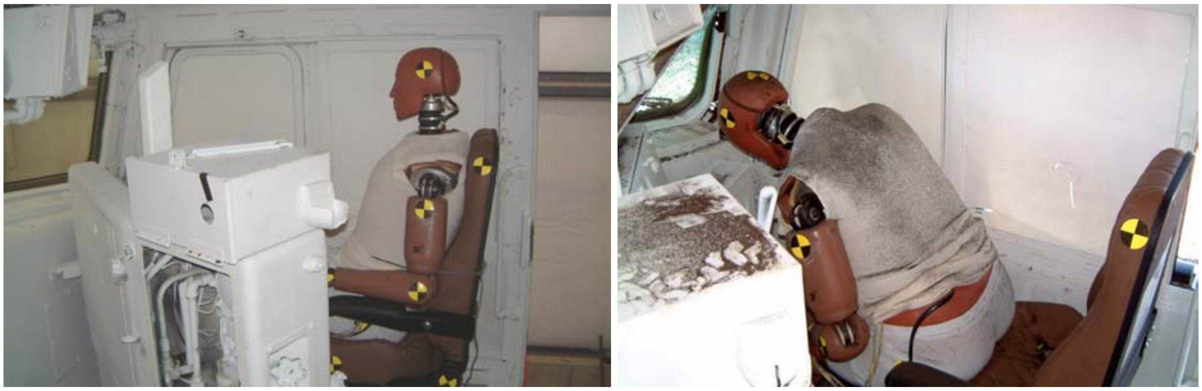


Figure 17. Test Dummy in Operator's Chair of Impacted Locomotive, Before and After Test

Figure 18 shows the test dummies in the three-position commuter passenger seat in the rear of the cab car. The inboard and center test dummies were Hybrid II test dummies with 50th percentile male stature, while the outboard test dummy was a Hybrid III test dummy with a 50th percentile male stature. (The principal difference between Hybrid II and Hybrid III dummies is that the Hybrid III includes a flexible neck with load cells, while the Hybrid II does not. This difference can be seen in the before test photo in Figure 18.) None of the NHTSA injury criteria threshold values was exceeded in this experiment during the test. Review of the high-speed movies taken during the test does show that the heads did rise over the seatbacks during the test, with the chests impacting the top of the seat backs.

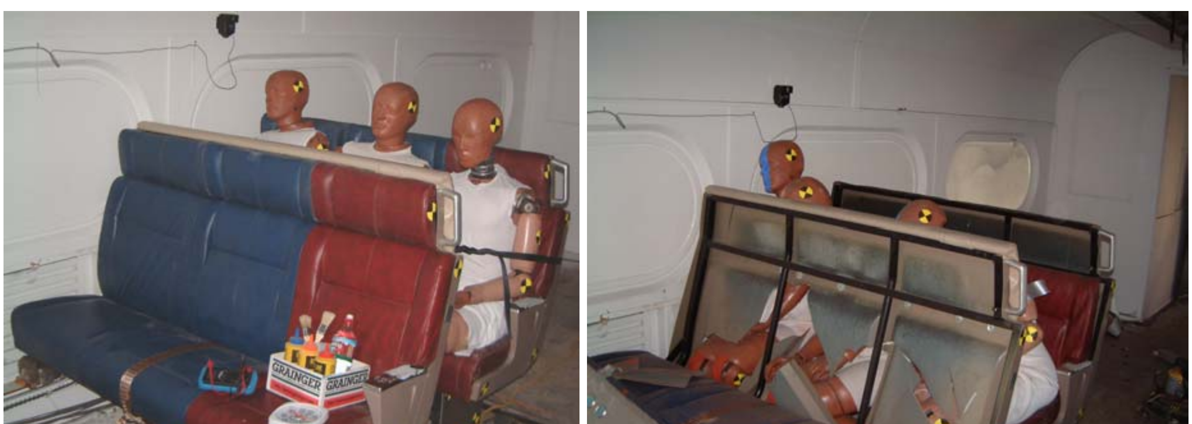


Figure 18. Test Dummies in Three-Position Commuter Passenger Seats in Cab Car, Before and After Test

Figure 19 shows the test dummies in the forward-facing inter-city passenger seats, that were located in the leading end of the first coach car behind the cab car. The test dummies in the leading row are restrained with lap and shoulder belts. The test dummies in the trailing row are not restrained. The test dummy in the inboard seat of the leading row was of 5th percentile female stature, and the test dummy in the outboard seat was of 95th percentile male stature.

Both dummies in the trailing row were of 95th percentile male stature. During the test, the dummy in the trailing row inboard seat fell into the aisle, and the head of the dummy in the outboard seat wedged in between the wall and the side of the seat ahead. The test dummies in the forward seat remained in their seats. None of the NHTSA injury criteria threshold values was exceeded in this experiment.

Figure 19. Test Dummies in Inter-City Passenger Seats in Cab Car, Before and After Test

Figure 20 shows the test dummies in the forward-facing rows of three-position commuter seat in the trailing end of the first coach car behind the cab car, before and after the test. The arrangement of this experiment was the same as the arrangement of the experiment in the cab car; the inboard and center test dummies were Hybrid II test dummies with 50th percentile male stature, while the outboard test dummy was a Hybrid III test dummy with a 50th percentile male stature. The dummy in the inboard seat exceeded the injury criteria value for the neck load. Like the experiment in the cab car, review of the high-speed movies taken during the test does show that the heads did rise over the seatbacks during the test, with the chests impacting the top of the seat backs.

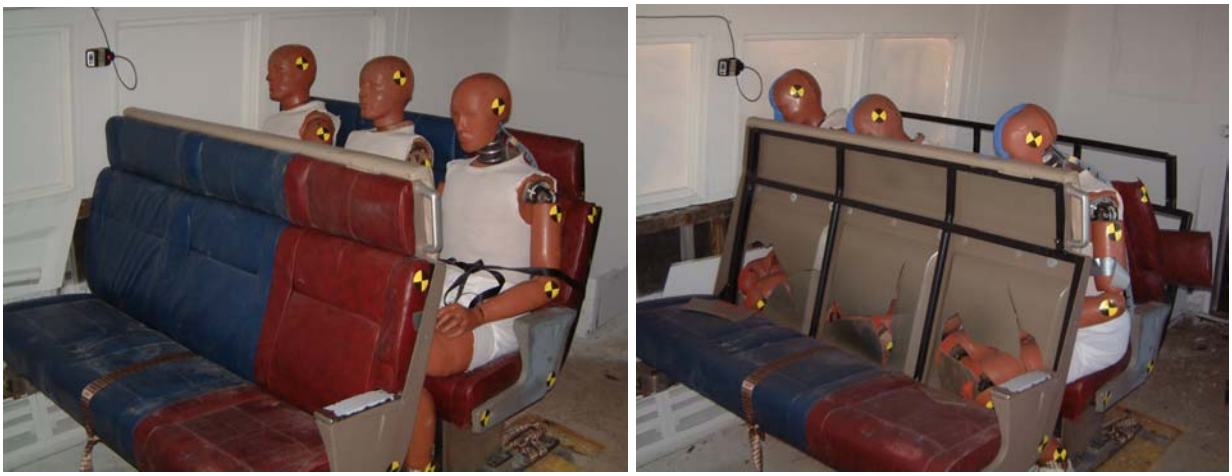


Figure 20. Test Dummies Three-Person Seats in Trailing Car, Before and After Test

The potential for injury and fatality may be greater in the train-to-train test than in previous in-line sled testing due to the lateral and vertical motions of the car during the train-to-train test, even though the unrestrained dummies in the train-to-train test impacted the seatback ahead of them at much lower speeds than dummies in 8 G sled tests [25]. Figure 21 shows a response during the two-car test for a test dummy initially in a forward-facing seat, without any restraints [25]. In this particular experiment, the test dummy's face impacted the upper seat back, followed by the head going over the top of the seat. Upon returning to its seated position, the chin caught on the top of the seat back. The middle photograph in Figure 21 shows all three of the dummies' heads above the top of the seatbacks.

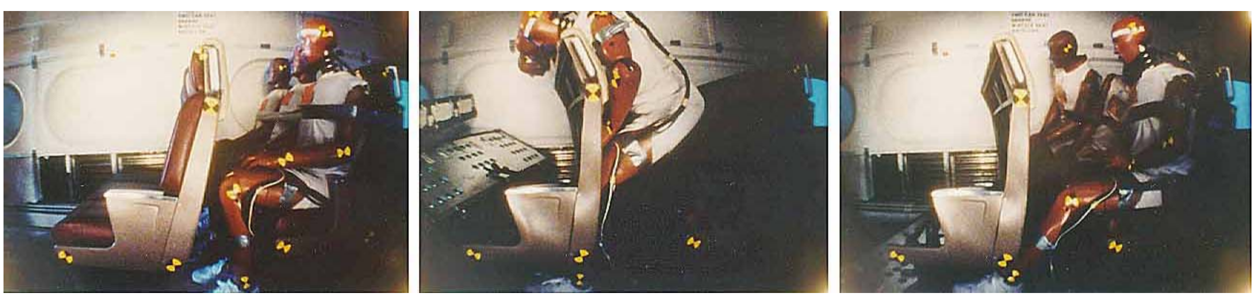


Figure 21. Time-Sequence for Forward Facing Rows of Seats, Trailing Car, Two-Car Test

In previous sled testing of the same model seat, lack of vertical motion led to the dummies' heads impacting the seatback near the top. The downward vertical motion of the car in the two-car test apparently influenced the dummies heads' to rise above the seatback. The forces and decelerations were within survivable limits in the sled testing, while the neck loads exceeded the limits used by the NHTSA in the two-car full-scale test.

3. TRAIN-TO-TRAIN TEST MEASUREMENTS AND ANALYSIS RESULTS

Several techniques have been used to analyze the test data. These analyses techniques were chosen to develop selected information from the test data. To estimate the amount of energy dissipated through crushing of the equipment and the amount of energy associated with the override of the locomotive by the cab car, energy and moment calculations were carried out. To evaluate the distribution of crush among the equipment and the longitudinal decelerations imparted to the test dummies, a one-dimensional train model was developed and exercised. The override of the locomotive by the cab car, the sawtooth lateral buckling of passenger cars, and the lateral and vertical accelerations imparted to the test dummies were evaluated with a three-dimensional train model.

The energy dissipated by crushing and the energy required for the cab car to override the locomotive can be calculated from relatively simple equations. These and other energy and moment values indicate what features of the collision have the greatest influence on its outcome and provide checks for more detailed models.

The crush of the cab car and the longitudinal decelerations of all the cars in both trains can be captured with a one-dimensional model because the vertical and lateral motions of the cars in the train are small compared with the longitudinal motion. During the test, both trains traveled longitudinally approximately 140 feet, while the center of gravity of the cab car rose approximately five feet, and traveled laterally approximately one foot. The lateral and vertical motions were less than 5 percent of the longitudinal motions. In other words, the longitudinal motions greatly influenced the vertical override and lateral sawtooth buckling of the train, but the override and sawtooth buckling did not greatly influence the longitudinal motion.

In order to simulate the vertical motions of the equipment associated with override of the locomotive by the cab car, and to simulate the lateral motions of the equipment associated with the sawtooth buckling of the cab car-led consist, a three-dimensional model is necessary. The measurements made with the test dummies indicate that the lateral and vertical motions of the cars significantly influence the response of the dummies.

The one-dimensional lumped-parameter model used to analyze the test data includes a single mass for each car and locomotive, connected by non-linear force-crush characteristics developed from the single-car, two-car, and train-to-train test data. The three-dimensional model includes separate masses for each of the trucks, as well as masses for each of the carbodies. This model included suspension elements connecting the carbodies and trucks. The data for the cab and first two coach cars' suspension elements were developed from the 'shake and bake' test conducted as part of the single-car test [14]. The data for the locomotives, freight cars, and T-7 were developed from available information. Both models are described in more detail in Appendix A.

3.1 ENERGY

Table 3 lists the initial kinetic energy and estimates of the energy dissipated in crushing of the equipment, by braking and sliding of the equipment on the ground, and the energy required for the cab car to override the locomotive. Crushing of the car structures dissipated approximately half of the initial energy, and the remaining half was dissipated by the braking of the initially standing consist and sliding on the ground of the initially moving consist. The energy dissipated in crush was estimated from conservation of energy and momentum, assuming that the crush was perfectly plastic and neglecting the influence of braking during the impact. The energy required for the cab car to override the locomotive was returned during the test when the cab car slid off the locomotive, back to the ground. This energy was calculated as the energy required to lift the center of gravity of the cab car body five feet off the ground.

Table 3. Initial Kinetic, Crush, Braking, and Override Energies

Energy	Value
Initial Kinetic Energy	19.2×10^6 ft-lbs
Energy Dissipated Through Crushing of Equipment	9.6×10^6 ft-lbs
Energy Dissipated Through Braking/Sliding	9.6×10^6 ft-lbs
Energy Required for Override	0.20×10^6 ft-lbs

As can be seen in Table 3, the energy required for the cab car to override the locomotive was approximately 1 percent of the initial kinetic energy, and about 2 percent of the energy dissipated by crushing of the equipment structures.

3.2 TRAIN LONGITUDINAL MOTIONS

Table 4 lists the amount of underframe crush the cab car sustained as a result of the test, and the amounts of crush predicted with the one-dimensional and three-dimensional models. The one-dimensional model slightly overestimates the crush because the energy went into override in the test goes into crush in this model. Since the amount of energy associated with override is small, the associated error is also small – on the order of 2 percent. The three-dimensional model closely predicts the amount of crush observed in the test.

Table 4. Cab Car Crush Measured in Test and Predicted with One- and Three-Dimensional Models

	Crush
Test Result	21.75 feet
1-Dimensional Model Prediction	22.5 feet
3- Dimensional Model Prediction	21.0 feet

Figure 22 shows the deceleration time-history of the cab car, for the first second of the impact, as measured during the test, and as predicted with the one-dimensional and three-dimensional models. The one-dimensional model closely predicts the peak deceleration and the general character of the deceleration. The greatest disagreement occurs at approximately 0.2 second, when the cab car began to override the locomotive. As the front of the cab car rose, the rear was lowered causing the load path to shift between the cab car and the first coach car. As a result of this shift in load path, the load pushing the cab car from behind was reduced for a brief period of time, momentarily increasing the deceleration of the cab car. This shift in load path is not currently included in either the one-dimensional or three-dimensional models. As a result, after 0.2 second the model predictions and test results are out of phase; although there is otherwise close agreement between the models and the test data. Graphs of the longitudinal deceleration time-histories of the other cars, with test data and analyses predictions, in the test are included in Appendix A.

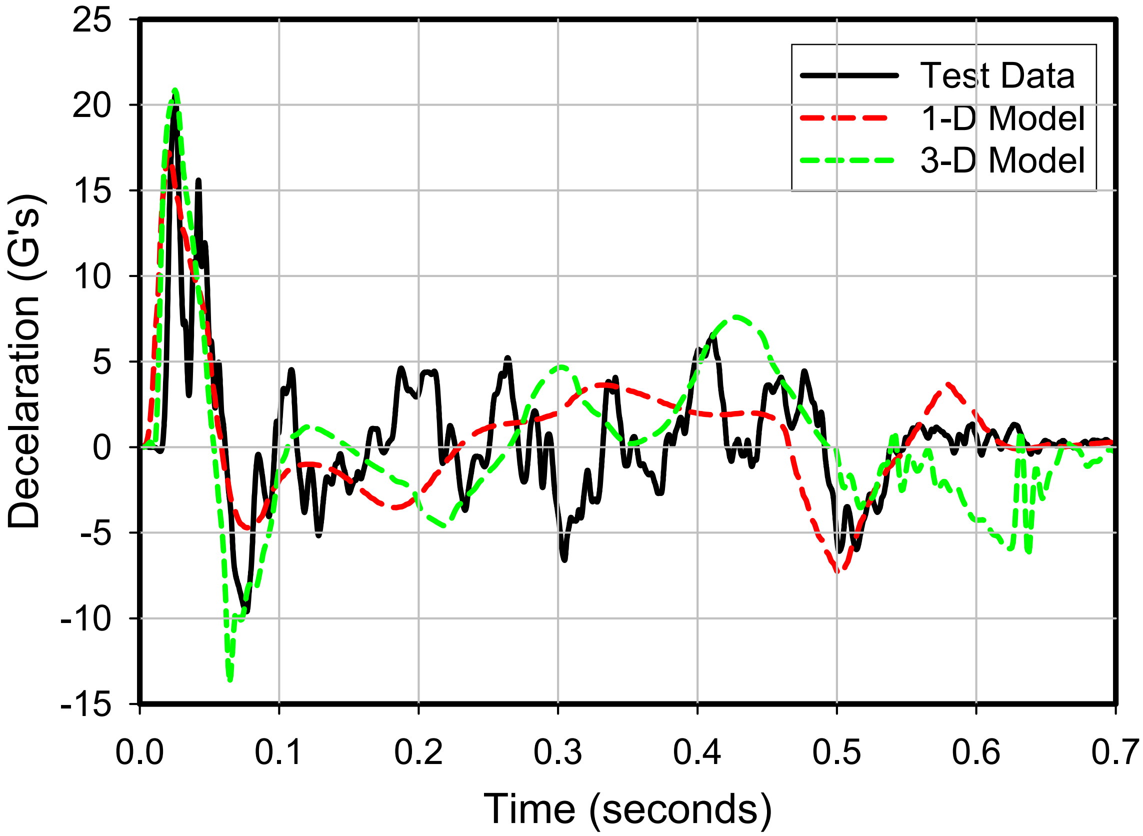


Figure 22. Longitudinal Deceleration Time-History of Cab Car, Test Measurement, Single-Dimensional Model, and Three-Dimensional Model Predictions

3.3 COLLIDING EQUIPMENT INTERACTION

Figure 23 shows the range of possible interactions between the colliding cab car and locomotive:

- The cab car overrides the locomotive
- The locomotive overrides the cab car
- The cab car and locomotive deflect past each other
- The cab car and locomotive remain engaged

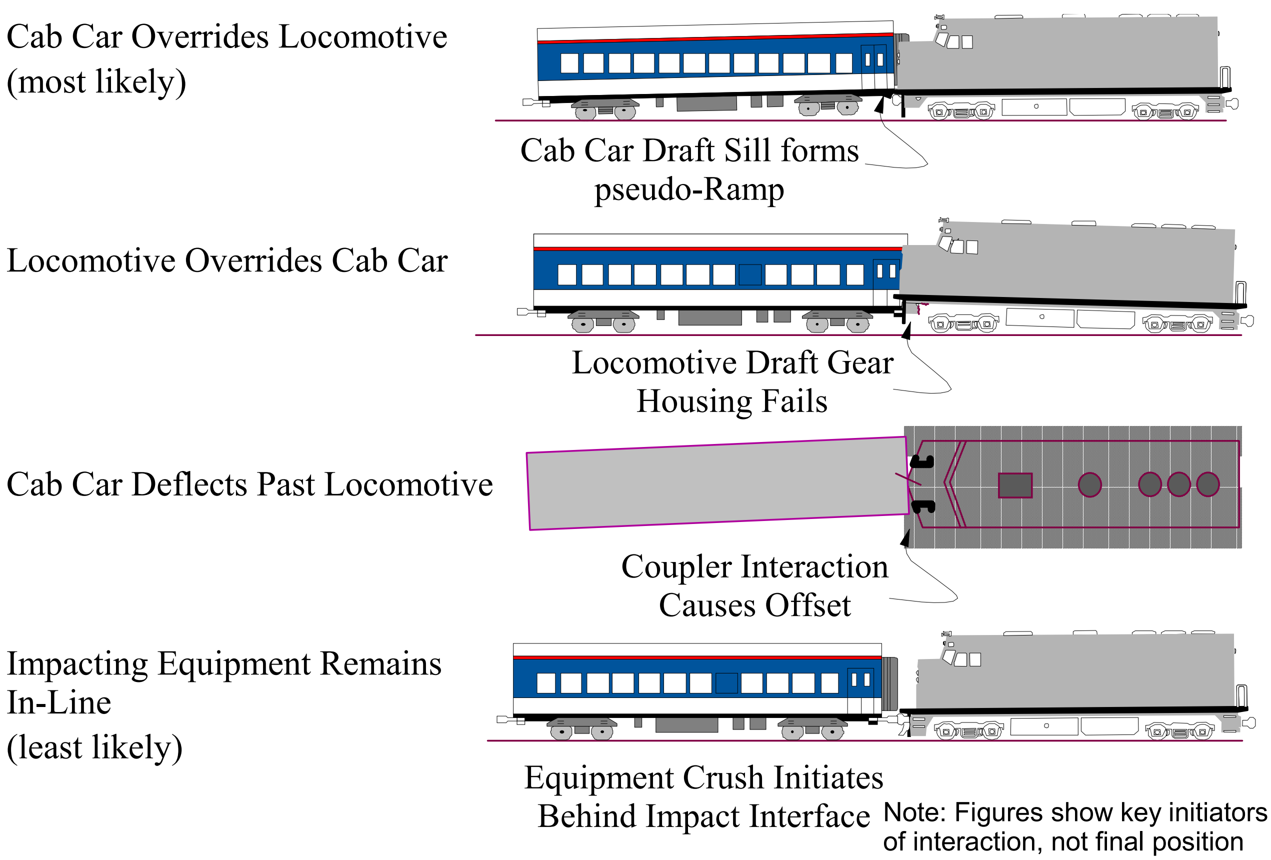


Figure 23. Potential Modes of Colliding Equipment Interaction

The interaction observed during the test was principally the cab car overriding the locomotive, with some amount of lateral deflection. This override was apparently due to the cab car structure initially crushing in a similar manner as it did during the single car and two car tests [14, 17, 26]. In the single car and two car tests, the structures crushed in such a way as to cause the impacted ends of the cars to rise. The cab car in the train-to-train test was being pushed from behind through the coupler and buffer beam; when the front end of the cab car rose, a vertical moment arm developed between the force crushing the cab car at the lead end and pushing it from behind. The moment due to the longitudinal forces was sufficiently large to overcome the weight of the cab car, and continue its upward pitch, allowing the cab car to override the locomotive.

As a result of the lateral deflection that occurred during the test, the right sidewall of the cab car was crushed, while the left sidewall remained nearly intact. This laterally deflection apparently was initiated by the interaction of the couplers; after the test the locomotive coupler was pushed to the extreme left, with some damage to the bellmouth. At impact, the knuckles of both couplers were closed; both the locomotive and cab car couplers moved to the left (with respect to the forward direction of the equipment), forming a lateral ramp. The amount of lateral displacement of the cab car was small compared with its vertical displacement. The center of gravity of the cab car rose approximately five feet and moved laterally approximately 1 foot during the impact.

A relatively minor change in initial conditions may have allowed the locomotive to override the cab car. The estimated maximum load that the locomotive's draft gear housing can support [27], approximately 3000 kips, is close to the load required to initiate crush of the cab car underframe at 2750 kips. If the load required to shear the locomotive's draft gear housing had been somewhat lower than estimated, then the locomotive would have overridden the cab car.

For the cab car and the locomotive to remain engaged, the load at the impact interface would have to be relieved before significant crush of either the cab car or locomotive could occur. This could occur by the trailing equipment buckling out laterally, or by the crush initiating behind the impact interface, as occurred in the recent locomotive-led freight train collision with a cab car-led commuter train in Placentia, California [10].

3.4 TRAIN VERTICAL MOTIONS

The train vertical motions include the override of the locomotive by the cab car, as well as the response of the each of the cars on their suspensions. Figure 24 shows the results of the three-dimensional model at similar times as for the pictures from the test shown in Figure 12. As can be seen by comparing the Figures 24 and 12 side by side, the model results compare closely with the test results.

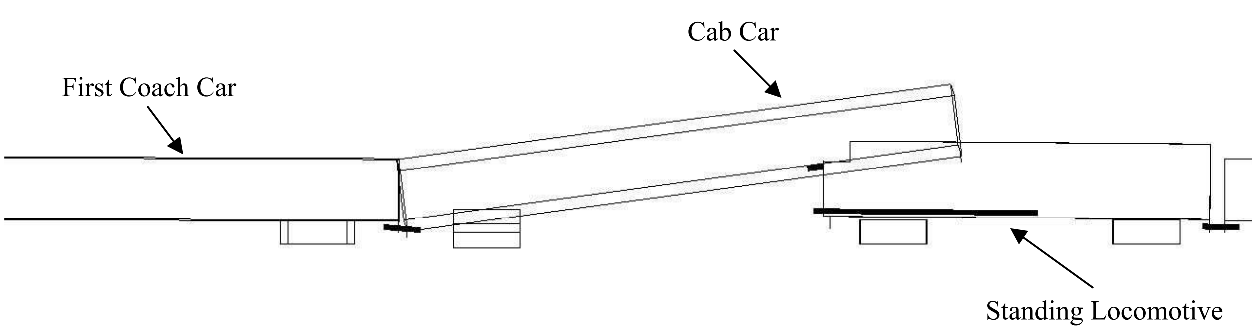


Figure 24. Plan View Schematic(s) of Coupled Car Interaction, Model Results

Figure 25 shows the pitch angle of the cab car as measured during the test and as evaluated with the three-dimensional model. Up to 0.6 second there is close agreement between the model predictions and the test measurements. During the tests, from approximately 0.6 second to 0.7 second, the cab car rode up the window structure of the locomotive onto its roof. The model uses heuristic elements to represent the short hood, window structure, and roof of the locomotive.

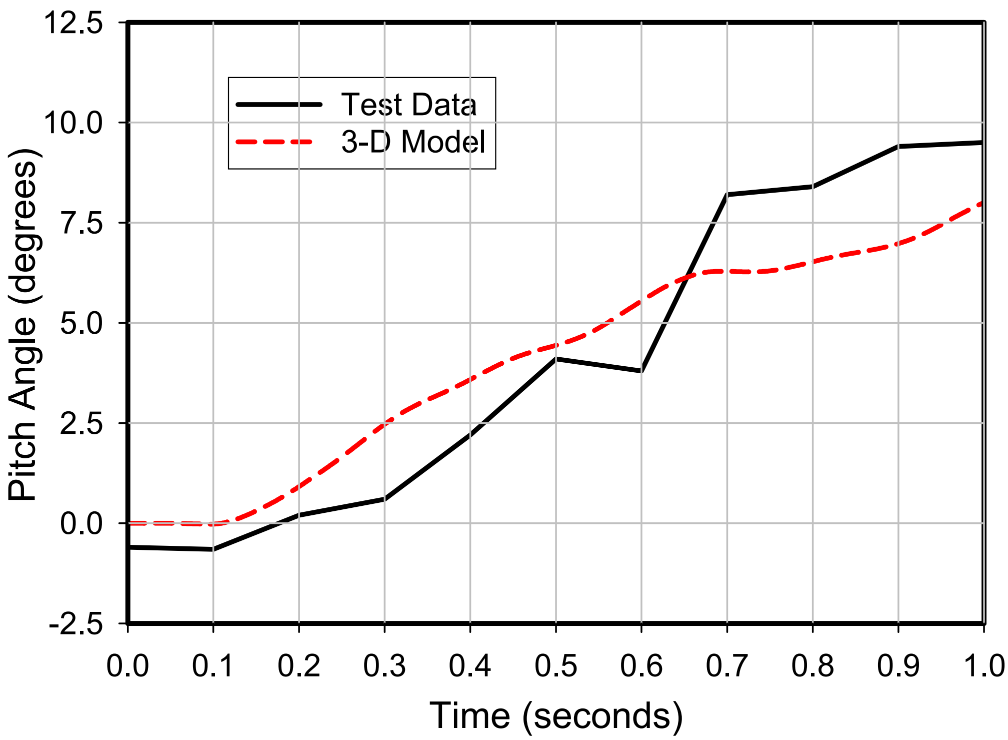


Figure 25. Pitch Time-History of Cab Car, Test Measurement and Three-Dimensional Model Predictions

3.5 TRAIN LATERAL MOTIONS

The lateral response of the train includes the lateral motions of the cab car and impacted locomotive as well as the sawtooth buckling of the passenger train. During contact, the maximum lateral displacement of the end of the cab car relative to the locomotive was approximately two feet. Most of the cab cars lateral displacement occurred when the two trains separated, and the cab car rolled as it slid off the locomotive. Figure 26 shows a schematic of the model results for the car at maximum lateral displacement (and at maximum override) at approximately 2 seconds after the impact. As can be seen in Figure 25, the model and test results agree closely.

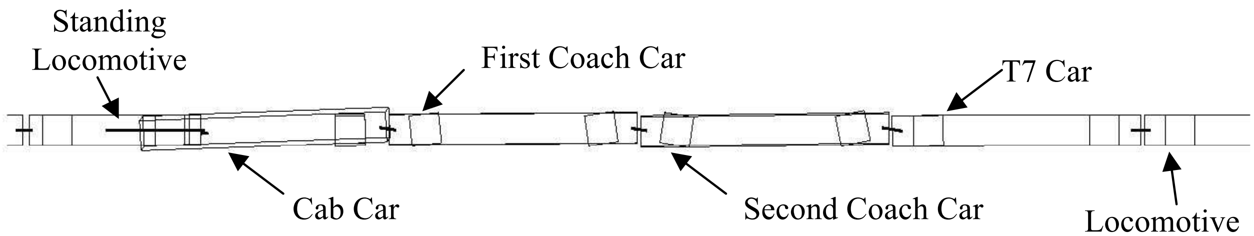


Figure 26. Elevation View Schematic Train Buckling, Model Results

Figure 27 shows the yaw angle of the cab car as measured during the test and as evaluated with the three-dimensional model. The model results are delayed compared with the test predictions, but are otherwise close. The jog seen in both the test data and the model predictions at approximately 2.5 degrees yaw is associated with the transition from sawtooth lateral buckling to large displacement lateral buckling. The approach used in the model is similar to a perturbation analysis for stability: the model requires an initial perturbation. This perturbation reflects the natural differences in lateral displacements between cars due to the cars response to the track. This perturbation is only present between the locomotive and the cab car. Including perturbations between the coach cars would likely bring the timing of the yaw time-history into closer agreement with the test data.

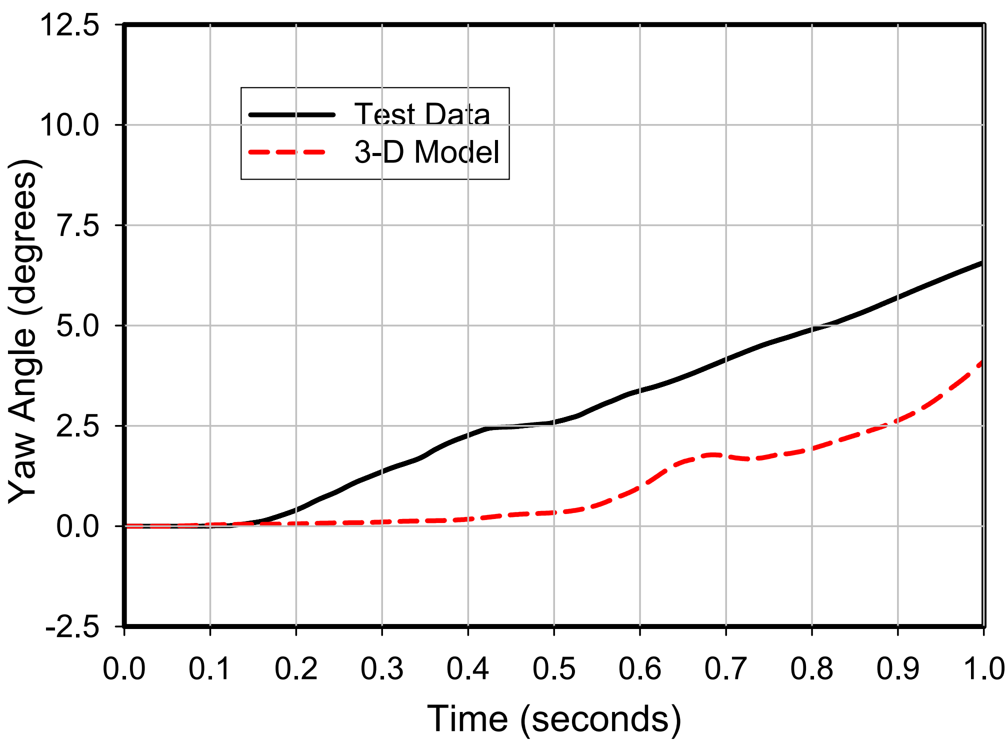


Figure 27. Yaw Angle Time-History of Cab Car, Test Measurement and Three-Dimensional Model Predictions

3.6 OCCUPANT ENVIRONMENT

The longitudinal, vertical, and lateral decelerations of the cars, along with the interior features of them, can make up the occupant environment during a collision. The lateral and vertical decelerations are small compared with the longitudinal deceleration; however, the lateral and vertical decelerations have a strong influence on unrestrained test dummy response. During the train-to-train test, for the unrestrained dummies in the forward-facing inter-city passenger seats in the first coach car, the vertical and lateral motions led to one dummy's head becoming wedged in between the sidewall of the car and the seatback ahead, and the adjacent test dummy being thrown into the aisle. For the unrestrained dummies in the forward-facing three-position commuter passenger seats, the vertical motions of the car resulted in the head's of the dummies missing the seatback ahead, and the chest's impacting the seat. This mode – where the chest impacts the seatback ahead rather than the head – results in high loads on the neck. The load on the aisle-side dummy in this experiment exceeded the NHSTA criteria threshold value. The unrestrained dummies in the forward-facing three-position commuter passenger seats in the cab car experienced a similar mode, although the neck loads did not exceed the NHTSA criteria threshold value. The effect of the lateral and vertical motions of the cars on unrestrained occupants can cause them to impact the interior in an unfavorable manner which can potentially cause injury and fatality, even at a relatively low longitudinal deceleration.

Although it is an incomplete measure for an unrestrained occupant, secondary impact velocity gives some indication of the relative severity of the occupant environment. The secondary impact velocity is the velocity at which an unrestrained occupant would impact the interior. The secondary impact velocity is computed from the deceleration-time history of the car, but provides a more appropriate means of comparison. The deceleration-time history can contain high values for a very short duration, which have little influence on the occupant response, but can make a deceleration time history appear to be severe when it is not. Conversely, a deceleration-time history may have a relatively high average value, and relatively low peak value, appearing to be benign, when in fact it is severe to the occupant.

Figure 28 shows the velocity of an unrestrained occupant relative to the car, for the distance the occupant has traveled inside the car, for the single-car test, two-car test leading car, and the train-to-train test cab car. The plot shows that the occupant environment in the single car test was the most severe, and the environment in the train-to-train test was least severe.

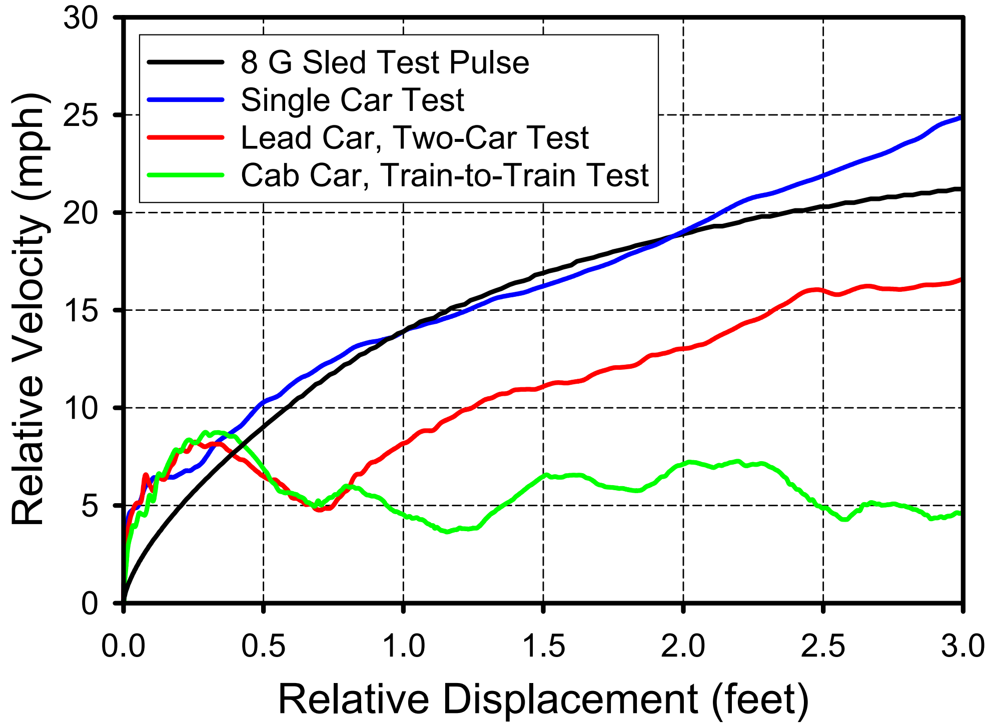


Figure 28. Secondary Impact Velocity, Single-Car Test, Two-Car Test Leading Car, and Train-to-Train Test Cab Car, Computed from Test Measurements

Figure 29 shows the three-dimensional model results and train-to-train test results for the secondary impact velocities for all of the cars in the cab car led consist, and the impacted locomotive.

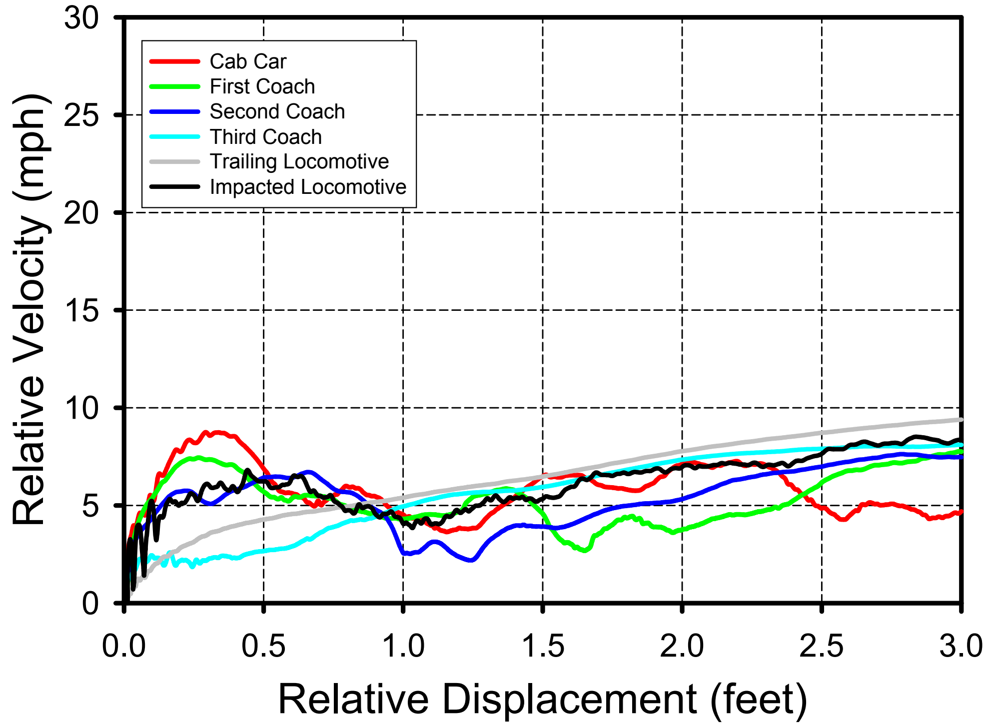


Figure 29. Secondary Impact Velocities, Cab Car Led Train and Impacted Locomotive, Train-to-Train Test

4. DISCUSSION

The train-to-train test was the third of three tests intended to define the performance of current-design equipment in in-line collisions. The first test consisted of a single passenger car impacting a fixed barrier, with the principal objective of measuring the force required to cause significant crush of the car and to observe the geometry of the crushed structure. The second test consisted of two-coupled passenger cars impacting a fixed barrier, with the principal incremental objective of measuring the interaction of the coupled cars, i.e., the kinematics of the coupling during the impact and the influence of the trailing car on the leading cars deceleration. The principal incremental objective of the train-train-test was to observe the interaction of the colliding equipment and to measure the environments experienced by the test dummies, as well as its responses.

During the train-to-train test, the cab car overrode the locomotive; the underframe of the cab car sustained approximately 22 feet of crush and the first three coupled connections sawtooth buckled. The short hood of the locomotive remained essentially intact, while there was approximately 12 inches of crush of the windshield center post. There was nearly no damage to the other equipment used in the test. Nearly all of the damage was focused on the cab car, with relatively modest damage to the locomotive.

Preliminary analyses of the train-to-train structural and occupant protection measurements have been completed. Analysis predictions of the crush and decelerations of the cars compared closely with test measurements. The structural measurements are currently being used to refine simulation models. The occupant protection measurements are being used to evaluate the influence of the vertical and lateral accelerations on occupant response, by comparing them with previous sled test measurements. The cab car operator's compartment was crushed, the space for ten rows of seat was lost in the cab car, and life-threatening injury values were measured by the test dummies in the first coach car.

Preparations are underway for single-car, two-car, and train-to-train tests with CEM equipment. For the train-to-train test of crash energy management equipment it is anticipated that the car crush will be distributed among the ends of all the cars. As a result, there should be no intrusion into the occupant volume. In the train-to-train test of conventional equipment, the crush was focused on the leading end of the leading car, resulting in loss of occupant volume for the first ten rows of passenger seats. For the CEM equipment, there should be no loss of occupant volume for the passengers. There is potentially loss of volume for the operator; however, means of protecting the operator, such as an operator's cage that gets pushed back into a utility closet in the event of a collision, are being investigated.

The occupant environment during the train-to-train test of the CEM equipment is expected to have slightly higher longitudinal decelerations, but lower vertical and lateral accelerations than during the train-to-train test of the conventional equipment. Overall, the occupant environments in the two tests are expected to be similar in terms of the likelihood of occupant injury.

Full-scale tests based on a grade-crossing collision with a heavy rigid object have also been implemented. These tests were used to evaluate the end structure of the cab car above the floor. Two such tests were conducted, one of a conventional cab car and another of a cab car with the end structure vertical elements – the corner posts and collision posts – tightly tied together with transverse elements. These tests were performed on June 4 and June 7, 2002 [28, 29].

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APPENDIX A: TEST REQUIREMENTS

The objectives of instrumenting the rail vehicles in the train-to-train test are to record the gross motions of the vehicles and components of the vehicles, and use this information to quantitatively describe characteristics of the collision. This appendix provides a summary of instrumentation details and why specific instrumentation was implemented.

Prior to this test, two tests for existing-design passenger rail equipment have been conducted. This test is the third in a series of tests to measure the crashworthiness performance of existing design equipment, addressing a locomotive led train colliding with a cab car led passenger train on tangent track. Unlike the single and two-car impact tests where the vehicles were impacted into a fixed wall, additional information is now desired for the interactions between the colliding consists.

General characteristics that need to be measured include initial geometry of the colliding vehicles, crush of the vehicles structure, and response of the vehicles on their suspension. Critical measurements used to determine these general characteristics for the train-to-train test include:

- crush and override of the colliding cars
- lateral buckling of coupled cars
- trajectories of all vehicles in the standing and moving consist
- measurement of locomotive operator and passenger car occupant environments.

The required information to be determined from instrumentation or photo documentation to evaluate the critical measurements include:

- longitudinal, vertical, and lateral forces developed between the colliding locomotive and cab car
- longitudinal, vertical, and lateral displacements developed between the colliding locomotive and cab car relative to each other
- mode of crush and/or override characteristics of the colliding cab car and locomotive
- elastic vibratory motions of all the vehicles
- gross motions of the cars and associated trucks, including the longitudinal, vertical, and lateral accelerations, velocities, and displacements
- displacements across the passenger trucks secondary suspension elements
- longitudinal forces developed between the coupled vehicles
- longitudinal, vertical, and lateral displacements of the couplers relative to the respective car bodies.

A.1 EQUIPMENT TESTED

The test was conducted on near level tangent track with a three-car standing consist (locomotive led with two coupled and ballasted hopper cars) being collided into by a 5-car moving consist (leading cab car with three coupler passenger coach cars and coupled trailing locomotive) traveling at approximately 30 miles per hour. A diagram of the rail vehicles used in the train-to-train test can be seen in Figure A-1 below. Table A-1 summarizes in more detail the vehicles used in the train-to-train collision test.

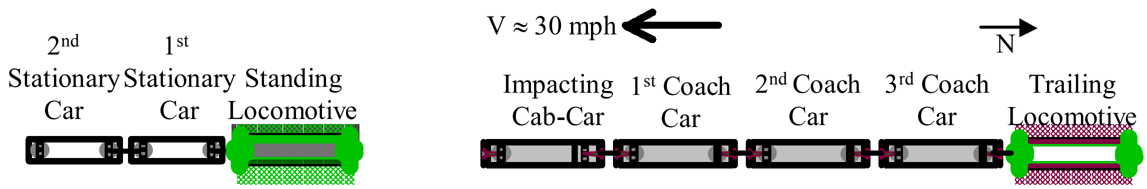

Figure A-1. Diagram of Rail Vehicles in Train-to-Train Test

Table A-1. Summary of Rail Vehicles Used in Train-to-Train Test

Stationary Consist		
Vehicle	**Description**	**Weight**
Standing Locomotive	End-Modified Passenger Locomotive	244,584 lb
1st Stationary Car	Ballasted Freight Hopper Car	312,598 lb
2nd Stationary Car	Ballasted Freight Hopper Car	78,459 lb
		Total = 635,641 lb
Moving Consist		
Vehicle	**Description**	**Weight**
Impacting Cab Car	End-Modified Passenger Car	75,014 lb
1st Coach Car	Budd MU Passenger Car	73,427 lb
2nd Coach Car	Budd MU Passenger Car	72,836 lb
3rd Coach Car	Passenger Car	148,944 lb
Trailing Locomotive	Passenger Locomotive	267,054 lb
		Total = 637,275 lb

The colliding cab car used in the testing is a Budd Pioneer car (also known as the SEPTA Silverliner I cars). These cars were designed and built in the late 1950's. The main structure (draft sill/body bolster/center sill) of the cars is similar to the main structure of most single-level cars currently in use. However, there were several changes in design practice related to the end structure (the collision posts and corner posts) between 1960 and 1999. The regulations issued by the FRA in May 1999 and the standards and recommended practices issued by American

Public Transportation Association (APTA) have resulted in further changes in practice for design of end structures.

The colliding cab car end structure design was modified to meet the Association of American Railroads Passenger Equipment Standards and Recommended Practices. The existing cab end structure (corner posts, collision posts, end beam, cross rail, any other lateral support members) was modified, without changing the car structure between the body bolsters, and with only minor modifications to the draft sill, side sills, roof plates and associated body sheathing.

The stationary locomotive used in the testing is a General Motors F40PH. These locomotives were designed and build after 1974. Additionally, the colliding end of the stationary locomotive was modified to bring the structure up to the current Locomotive Crashworthiness Requirement S-580 of the Association of American Railroads Safety & Operations Department Manual of Standards and Recommended Practices. This involved modifying forward facing sheeting on the short hood and collision posts with a different material having a greater thickness.

A.2 TRACK AND FIXTURES

The crash location was chosen to best represent typical tangent level railroad track. The rails themselves are laid on wooden ties directly into ballast on a raised earth foundation, typical of passenger track. The slope of the guideway was less than 0.1 percent, and the parallel rails had near zero crosslevel.

A.3 INSTRUMENTATION

Accelerometers, strain gages, displacement transducers, and high-speed film cameras were used to gather the data during the impact.

Accelerometers were used to make measurements in order to help determine:

- longitudinal, vertical, and lateral forces developed between the colliding locomotive and cab car
- longitudinal, vertical, and lateral displacements developed between the colliding locomotive and cab car relative to each other
- override characteristics of the colliding cab car and locomotive
- longitudinal forces developed between the coupled vehicles
- elastic vibratory motions of the carbodies
- gross motions of the cars and associated trucks, including the longitudinal, vertical, and lateral accelerations, velocities, and displacements.

Figure A-2 shows the location of the accelerometers for the colliding cab car in the train-to-train test. All the accelerometers were chosen to make measurements with adequate resolution, but some of the accelerometers at the impacting end will not survive the collision environment. All the longitudinal accelerometers had a range of at least ±400 G's, most of the vertical accelerometer ranges were ±200 G's, and most of the lateral accelerometer ranges were at least ±100 G's.

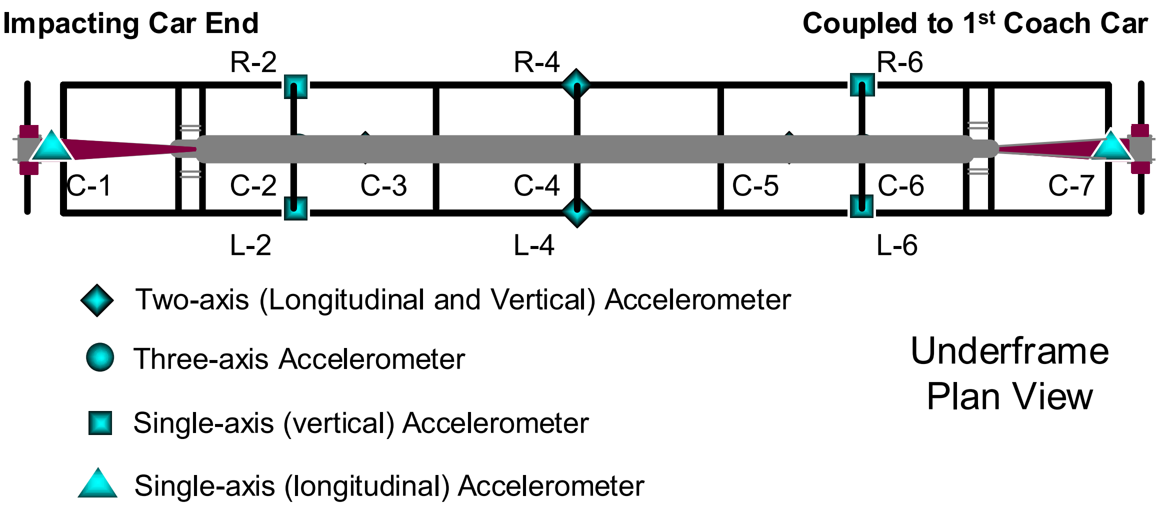

Figure A-2. Schematic Layout of Colliding Cab Car Accelerometer Locations

Even though the underlying deceleration to be measured was expected to be less than 50 G's, the accelerations measured by the accelerometers include a contribution from the gross motions of the car, a contribution from the elastic vibrations of the car, and a contribution from the vibration of the accelerometer on its mounting. All this contributes to measured acceleration several times greater than the underlying deceleration.

Figures A-3 through A-9 summarize the location of the accelerometers for remaining rail vehicles in the train-to-train test. All the accelerometers were chosen to make measurements with adequate resolution for the expected impact environment. All the longitudinal accelerometers had ranges between ±200 and ±100 G's, the vertical accelerometers had ranges between ±200 and ±50 G's, and the lateral accelerometers had ranges between ±100 and ±25 G's.

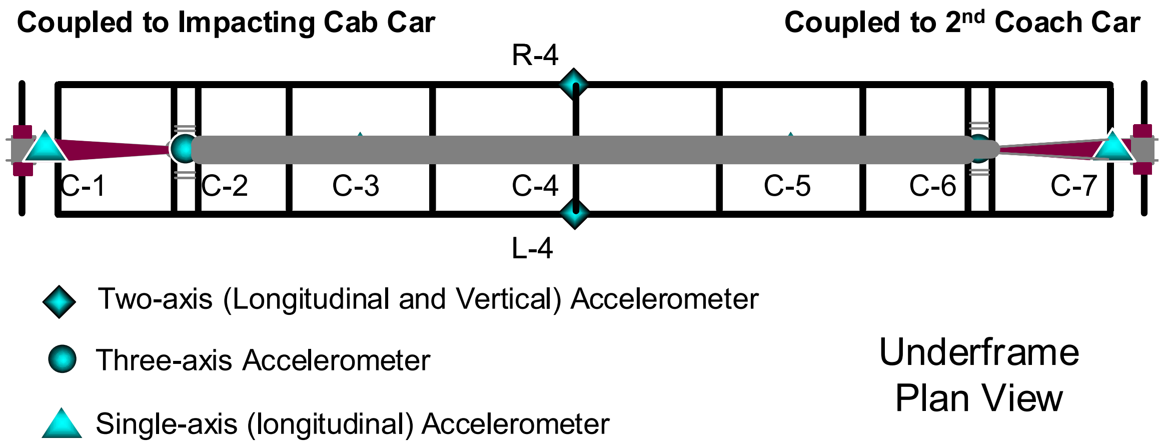

Figure A-3. Schematic Layout of 1st Coach Car Accelerometer Locations

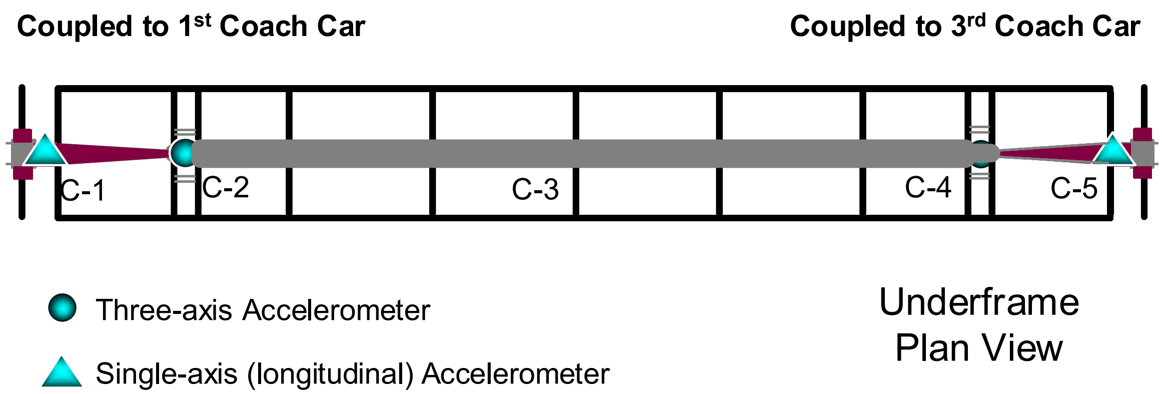

Figure A-4. Schematic Layout of 2nd Coach Car Accelerometer Locations

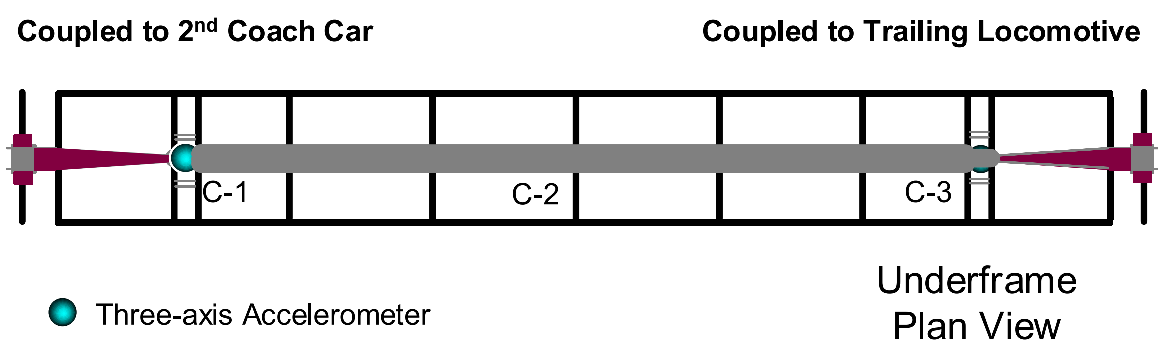

Figure A-5. Schematic Layout of 3rd Coach Car Accelerometer Locations

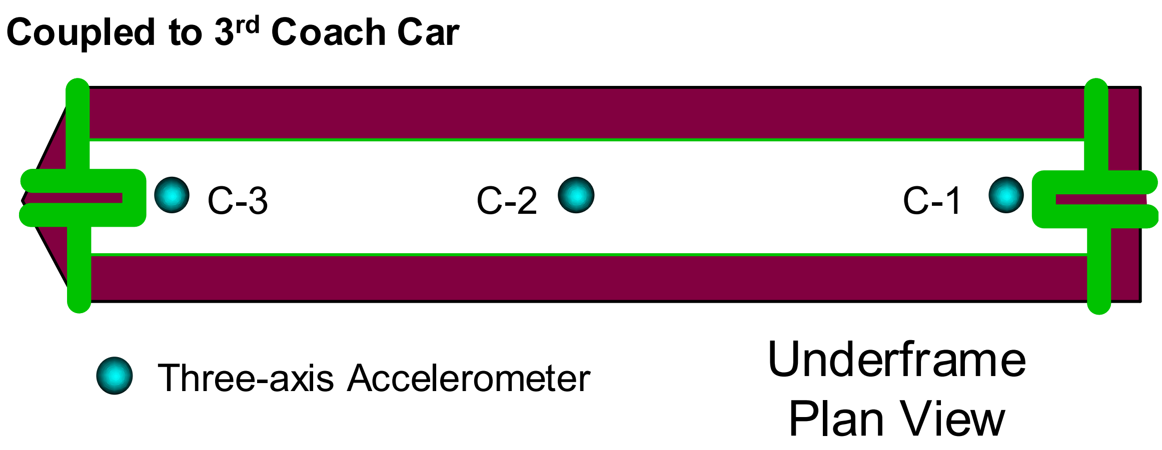

Figure A-6. Schematic Layout of Trailing Locomotive Accelerometer Locations

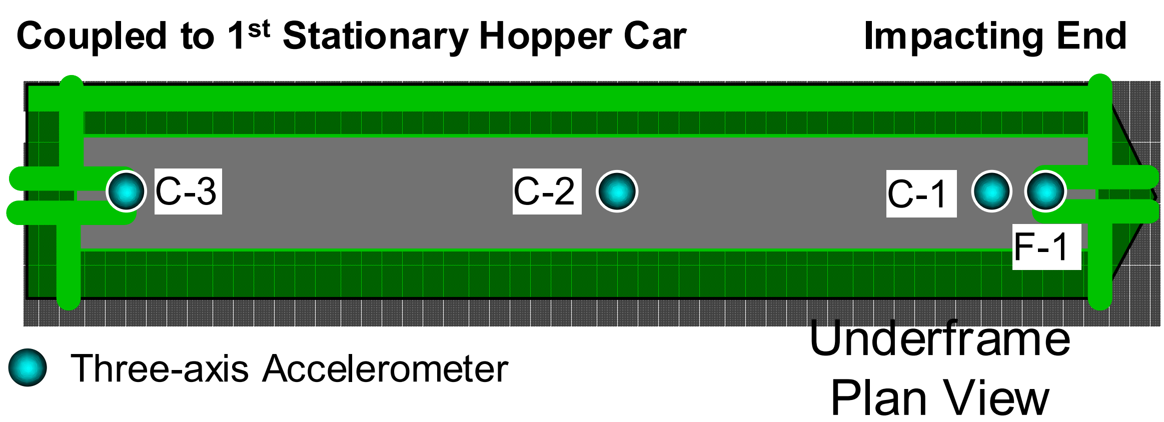

Figure A-7. Schematic Layout of Standing Locomotive Accelerometer Locations

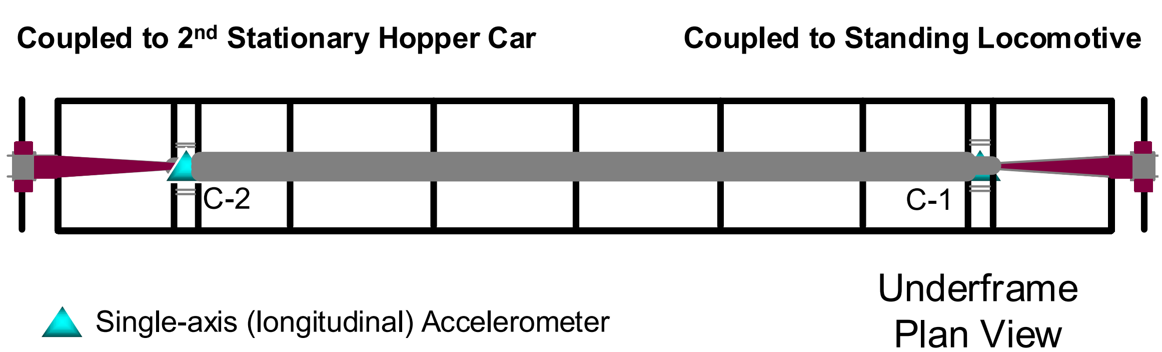

Figure A-8. Schematic Layout of 1st Stationary Freight Car Accelerometer Locations

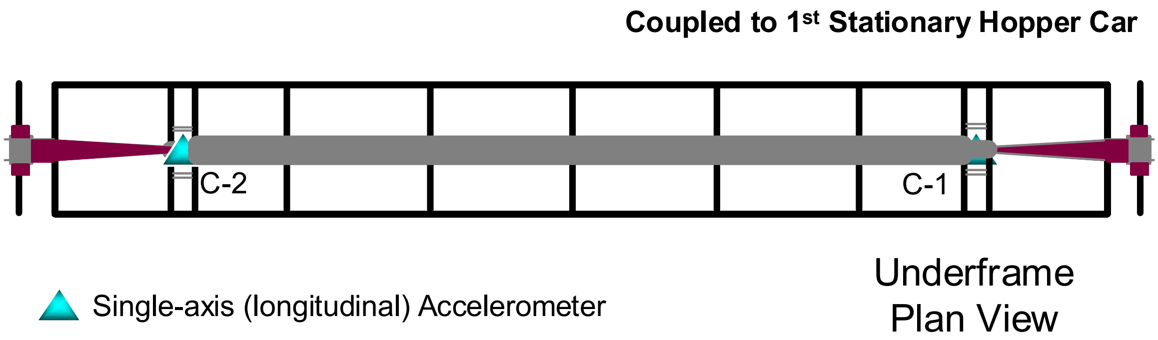

Figure A-9. Schematic Layout of 2nd Stationary Freight Car Accelerometer Locations

Because these contributions cannot be completely separated, there is some uncertainty in the post-processed force calculated from the accelerations, as well as in determining the vibratory modes of the vehicle. To assist in separating the vehicle structural characteristics, high speed cameras were used to record the collision from several viewpoints. A schematic and summary of the high speed film camera locations is presented in Table A-2 and Figure A-10. The film can then be used to determine the displacements of the car by photometric analysis. The photometric results provide a cross-check for the displacements computed from the acceleration measurements.

In all, the photometric analysis of the high speed film is used to determine the following data:

- gross longitudinal, lateral, and vertical displacement of the colliding cab car and colliding locomotive
- gross longitudinal displacement of all vehicles in the moving consist
- estimated longitudinal velocity of the moving consist
- timing and structural crush characteristics of the colliding vehicles
- timing of significant events for each consist during the collision, i.e. derailment.

Table A-2. Summary of High Speed Film Cameras used in Exterior Photo Documentation

Location	Camera View	Frame Rate in Frames Per Second
1	West Side of Consist – View of Impacting Cab Car and Locomotive	300
2	Overhead of Consist – View of Impacting Cab Car and Locomotive	500
3	East Side of Consist - View of Impacting Cab Car and Locomotive	300
4	East Side of Consist – View Between Impacting Cab Car and 1st Coach	300
5	East Side of Consist – View Between 1st Coach and 2nd Coach	300
6	East Side of Consist – View Between 2nd Coach and 3rd Coach	300
7	East Side of Consist – View Between 3rd Coach and Trailing Locomotive	300
8	Overhead of Consist – View Down Length from Behind Trailing Locomotive	300
9	East Side of Consist – Panning Camera of Impacting Cab Car and Locomotive	120
10	East Side of Consist – Close-Up View of Impacting Cab Car and Locomotive	500

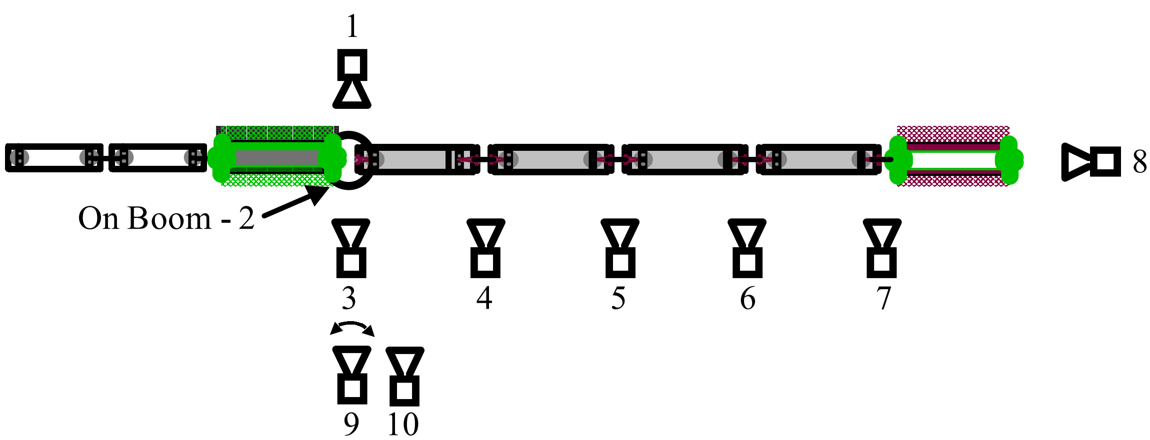

Figure A-10. Diagram of the Locations of High Speed Film Cameras for Photo Documentation

To ensure proper timing of the film information, all the cameras imprint a 100 Hz reference signal on the film so that accurate frame speed can be determined from post-test film analysis. All the exterior cameras will be started simultaneously from a central trigger several seconds before the impact, and strobe lights are flashed in the frame of each camera to indicate time zero, or impact of the standing locomotive and moving cab car. Four-inch diameter targets are also placed in several of the vehicles to facilitate post-test film analysis to determine speed and displacement of the vehicles during the impact.

Strain gages were also used on the impacting cab car and standing locomotive to help determine:

- loadings carried by the structural members
- timing of the members crushed during the collision.

The center sill, side sill, and cant rail of the impacting cab car had locations strain gages. On the standing locomotive, only the main sill had locations with strain gages.

Displacement transducers, string potentiometers, were used to measure the displacements across the trucks secondary suspension of the first three cars in the moving consist, as well as fixed on the couplers between the first four cars in the moving consist. These measurements provide:

- relative displacement of the carbody with respect to the trucks
- longitudinal, vertical, and lateral movement of the coupler between vehicles.

To determine the velocity of the moving consist at impact, a dual channel speed trap is installed to accurately measure the speed. Passage of a rod affixed to the vehicle will interrupt laser beams a fixed and known distance apart.

Tables A-3 and A-4 summarize the instrumentation, excluding high speed film cameras and speed trap, on each vehicle.

Table A-3. Summary of Moving Consist Instrumentation for Train-to-Train Test

Moving Consist	Accelerometers	Displacement Transducers	Strain Gages
Impacting Cab Car	***Car Body*** 9 Longitudinal 11 Vertical 3 Lateral ***Per Truck*** 1 Longitudinal 1 Vertical 1 Lateral	***B-End Coupler*** 1 Longitudinal 1 Vertical 1 Lateral ***Per Truck*** 2 Vertical on Secondary Suspension	***Center Sill*** 12 Locations ***Side Sill*** 6 Location ***Cant Rail*** 5 Locations
1st Coach Car	***Car Body*** 9 Longitudinal 5 Vertical 3 Lateral ***Per Truck*** 1 Vertical	***A and B-End Coupler*** 1 Longitudinal 1 Vertical 1 Lateral ***Per Truck*** 2 Vertical on Secondary Suspension	None
2nd Coach Car	***Car Body*** 5 Longitudinal 3 Vertical 3 Lateral ***Per Truck*** 1 Vertical	***A and B-End Coupler*** 1 Longitudinal 1 Vertical 1 Lateral ***Per Truck*** 2 Vertical on Secondary Suspension	None
3rd Coach Car	***Car Body*** 3 Longitudinal 3 Vertical 3 Lateral ***Per Truck*** 1 Vertical	***A-End Coupler*** 1 Longitudinal 1 Vertical 1 Lateral	None
Trailing Locomotive	***Car Body*** 3 Longitudinal 3 Vertical 3 Lateral ***Per Truck*** 1 Vertical	None	None

Table A-4. Summary of Standing Consist Instrumentation for Train-to-Train Test

Standing Consist	Accelerometers	Displacement Transducers	Strain Gages
Standing Locomotive	***Car Body*** 5 Longitudinal 5 Vertical 5 Lateral ***Per Truck*** 1 Longitudinal 1 Vertical 1 Lateral	***Per Truck*** 2 Vertical on Secondary Suspension	***Main Sill*** 12 Locations
1st Stationary Car	***Car Body*** 2 Longitudinal	None	None
2nd Stationary Car	***Car Body*** 2 Longitudinal	None	None

A.4 DATA ACQUISITION

On-board data acquisition systems were used to record the measurements from the accelerometers, strain gages, and displacement transducers. Battery powered Data Bricks provided 8-channels of data acquisition per brick, excitation to the strain gages and accelerometers, analog anti-aliasing filtering of the sensor signals, analog to digital conversion, and digital recording. Data from most all accelerometers, all strain gages, and most displacement transducers were recorded at a sample rate of approximately 8000 Hz, with 2 seconds of recording before the initial impact and 6 seconds of sensor recording after the initial impact. All the instrumentation used complies with most of SAE J211/1, Instrumentation for Impact Tests – the only deviation was that the data sample rating was slightly lower. Although this standard was developed for automotive impact testing, there is nothing equivalent, as yet, for railway vehicle impact testing and so this standard was used.

All the recorded data is synchronized with a time reference applied to all data acquisition systems simultaneously at the time of impact. This time reference comes from the closure of a tape switch on the front of the impacting cab car with the front of the standing locomotive. The switch closure will trigger each Data Brick and 2 seconds of pre-trigger data is recorded in the Data Brick. In all, 8 seconds of data is recorded.

APPENDIX B: POST PROCESSING OF DATA

A post processing procedure is applied based on experience from prior full scale impact tests of rail vehicles and recommendations of SAE J211/1, "Instrumentation for Impact Tests." The purpose of post processing is to scale and filter the data, determine zero levels, and perform mathematical operations that result in the information requested from the test. The different sensors of the instrumentation (accelerometer, strain gage, displacement transducer, and video camera) each provide useful measurements, and allow cross-checks of the test results. This section will briefly describe the post-processing of the different sensors.

All instrumentation is post-test filtered with a two-pass phaseless four-pole digital filter algorithm consistent with recommendations of SAE J211. All filtering precedes all nonlinear operations, such as calculation of injury indices. To facilitate valid comparisons between measurements, channel frequency classes are designated for the different test measurements, and are summarized in Table B-1.

Table B-1: Frequency Response Classes Used in Post-Processing of Full-Scale Impact Data

Test Measurement	Channel Frequency Class (CFC)
Vehicle Structural Acceleration for use in:	
Total Vehicle Comparison	60
Barrier Face Force	180
Integration for Velocity and Displacement	60
Vehicle Structural Strain	60
Vehicle Structural Displacement	60

From the accelerations measured, post processing consists of many intermediate steps to obtain the information above. A diagram of the primary steps in post processing is shown in Figure B-1. A dashed line is shown between the Acceleration Time-Trace and Force Time-Trace blocks, since all the accelerometers on an individual vehicle are not used in calculating the longitudinal forces.

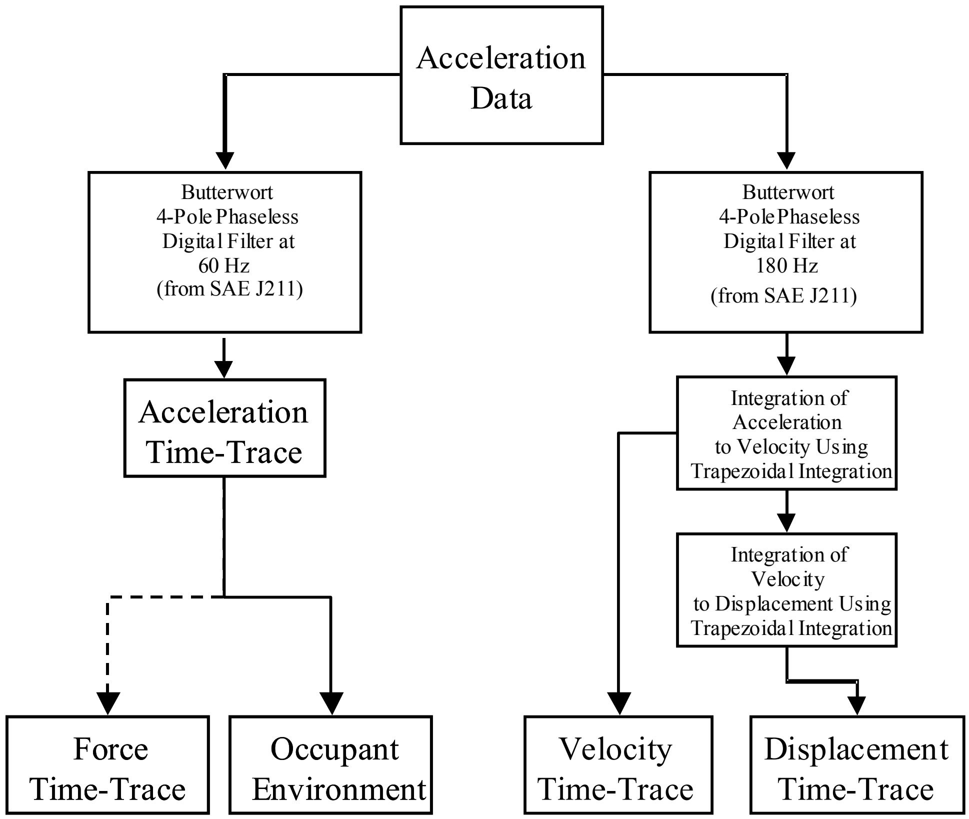

Figure B-1: Flow Diagram of Steps Used in Post Processing Acceleration Data

Each longitudinal, vertical, and lateral accelerometer initially has the offset adjusted using the transducers measurement before initial impact of the consists. The data is then either filtered with a CFC 60 for use in vehicle acceleration comparison or force calculation, or filtered with a CFC 180 for integration to velocity and displacement. Integration to velocity and displacement is calculated using the trapezoidal rule. An example of the integration of the representative accelerometer of the impacting cab car is shown in Figure B-2. For this location at the back of the vehicle, the peak filtered acceleration was 20.5 G, the velocity decreased from 30 mph to 7.2 mph, and the longitudinal displacement down the track was 127.1 feet in the 6 seconds following initial impact.

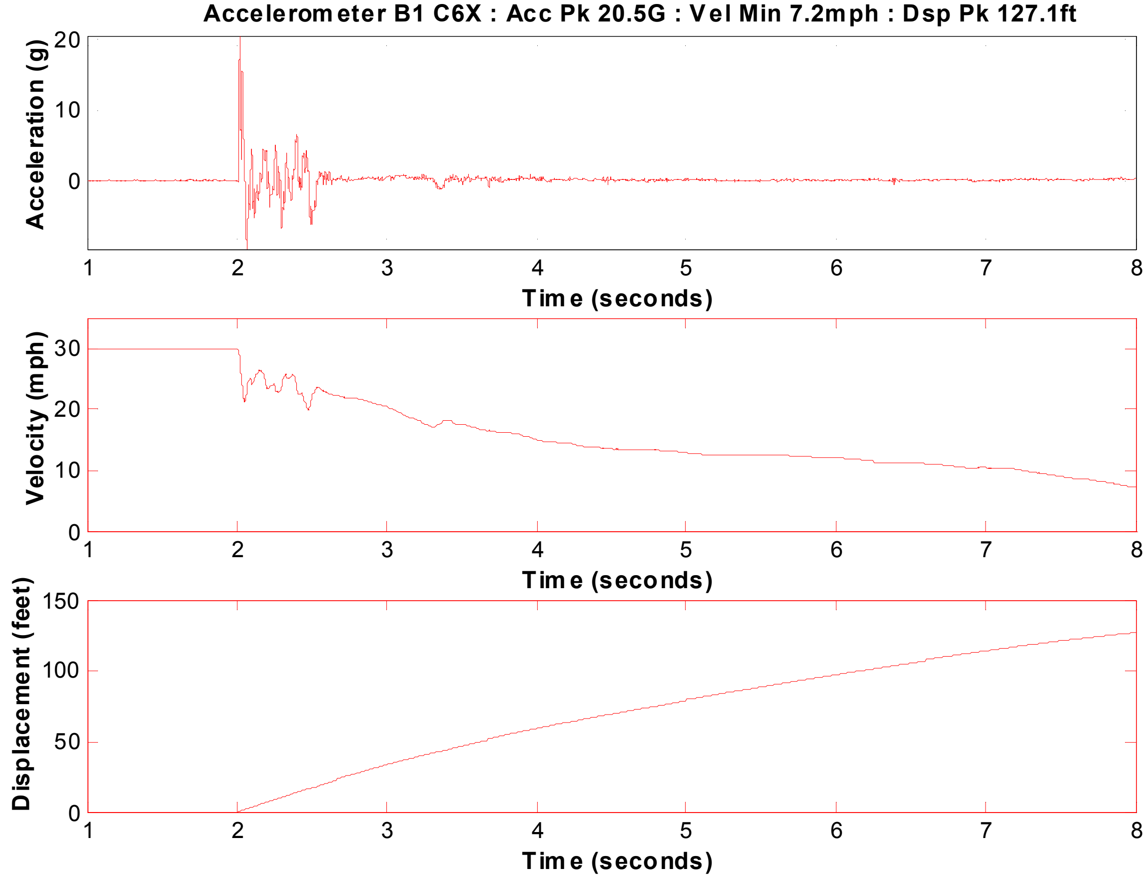

Figure B-2: Example of Integrating an Accelerometer to Obtain Velocity and Displacement

The longitudinal force acting between the coupled and impacting vehicles is calculated from the measured longitudinal accelerations of each vehicle. The force acting between vehicles is the sum of the forces contributed by each vehicle on one side of the interface between vehicles. For example, the longitudinal force acting on the lead end of the last vehicle in the train and on the front end of the second to last vehicle is the longitudinal acceleration of the last vehicle multiplied by its mass. The longitudinal force acting on the front of the second to last vehicle and on the back of the third to last vehicle is the acceleration of the second to last vehicle multiplied by its mass added with the acceleration of the last vehicle multiplied by its mass. The force acting at the impacting interface is the sum of the accelerations and masses for all the vehicles in the train. The force calculated from one side of the interface should be the same as the force calculated from the opposite side, however, errors in accelerometer measurement – which can creep in due to local vibrations of the carbody near the accelerometer, as well as due to the inherent accuracy tolerance of the accelerometer – result in some variations between the two calculations.

The occupant environment is described by the acceleration time histories of the cars, as well as by the relative velocity/relative displacement for an unrestrained occupant. From the same accelerometer used in Figure B-2, relative displacement and relative velocity are calculated and presented in Figure B-3. This plot provides an estimate of the velocity an occupant would be expected to have when contacting an object after traveling a certain distance after the impact. This is useful in comparing occupant environments of different vehicles, and other tests.

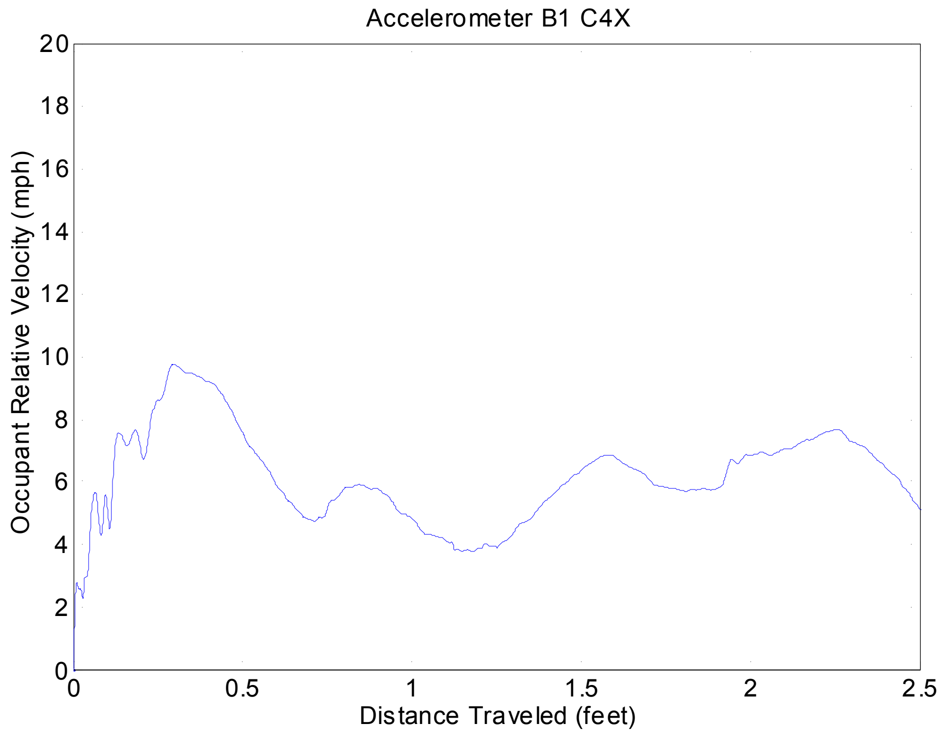

Figure B-3: Estimated Occupant Environment from Accelerometer Data in the Impacting Cab Car

Post-test computation of the strain gages and displacement transducers includes principally filtering and plotting the instrumentation results.

Post-test analysis of the film is valuable to determine vehicle displacements for comparison with and verification of the accelerometer data.

APPENDIX C: MODELS AND PREDICTIONS

C.1 MODELS

Two collision dynamics models were used to evaluate the train-to-train test results: a one dimensional model and a three-dimensional model. The one-dimensional model was initially developed to evaluate alternative crashworthiness strategies, performed in support of the development of the safety specifications for Amtrak's high-speed trainsets [3]. The three-dimensional model was initially developed to evaluate the tendency of passenger trains to buckle laterally during collisions [4].

C.1.1 SINGLE-DIMENSIONAL MODEL

Each car is represented by a single mass in the single dimensional model; each mass is only allowed to translate longitudinally in the model. The cars are connected to each other by force/displacement characteristics. A schematic of the one-dimensional train model is shown in Figure C-1.

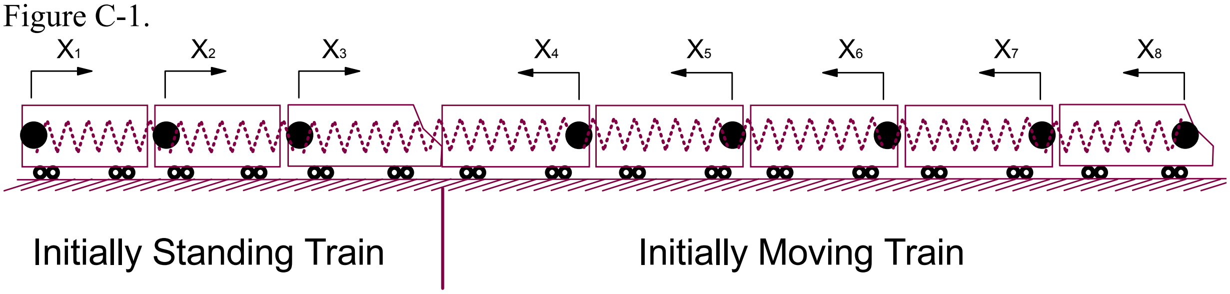

Figure C-1. Schematic of One-Dimensional Train Collision Dynamics Model

C.1.2 THREE-DIMENSIONAL MODEL

Each car is represented by a carbody mass and two truck masses in the three-dimensional model. Each of these masses is permitted translation in three directions – longitindal, lateral, and vertical -- as well as rotation in three directions – roll, pitch, and yaw.

The features included in the model of a conventional passenger car are shown in Figure C-2. The body of the car is supported by the suspension system attached to the trucks. The suspension stiffness is based on measurements during a 'shake-and-bake' test of the car used in the single-car test [16]. The truck elements are allowed to yaw relative to the car body about a vertical axis, which allows curving. The coupler element is allowed to pitch and yaw relative to the vehicle to which it is connected and is constrained from axial rotation.

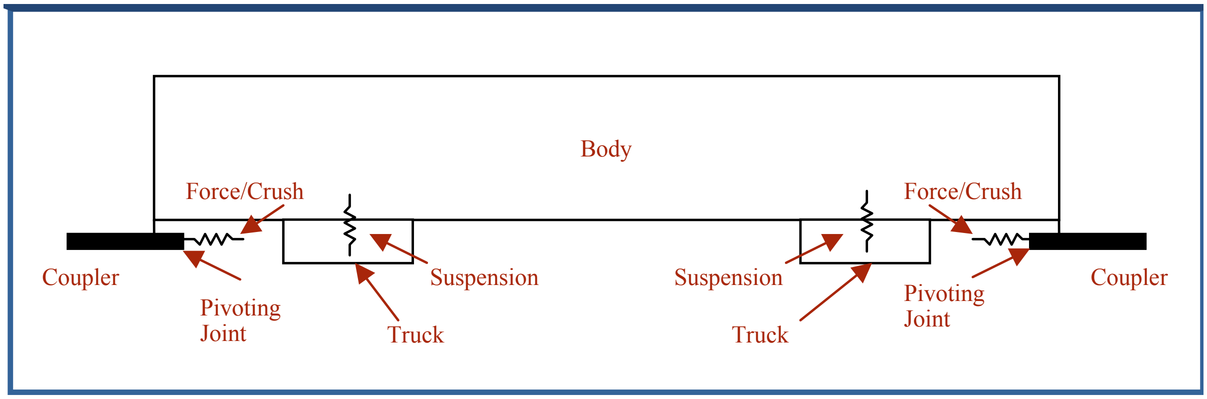

Figure C-2. Schematic of a Car from the Three-Dimensional Train Collision Dynamics Model

C.1.3 EQUIPMENT WEIGHT

The total weight of the locomotive-led train was 639,341 pounds and the total weight of the cab car-led consist was 637,275 pounds. The freight cars in the locomotive-led consist were ballasted such that the weight of the locomotive-led consist was approximately the same as the weight of the cab car led consist, to approximate more closely a collision between a cab car led passenger train and a locomotive-led passenger train. Table C-1 lists the weights of the locomotives and cars in the two trains.

Table C-1. Equipment Weights

Equipment	Weight (pounds)
Second Trailing Open Hopper Car	78,459
First Trailing Open Hopper Car	312,598
Lead Locomotive	248,284
Lead Cab Car	75,014
First Coach Car	73,427
Second Coach Car	72,836
Third Coach Car	148,944
Trailing Locomotive	267,054

C.1.4 FORCE/CRUSH CHARACTERISTIC

Figure C-3 shows the force/crush characteristic between the colliding cab car and locomotive used as input to the collision dynamics models and the force/crush characteristic calculated from the deceleration-time histories of the cars in the cab car-led train. The characteristic used as input to the models was derived heuristically from the characteristic based on the test data. The input force/crush characteristic was developed as a subjective best-fit to the force/crush characteristic and the force-time history based on measured data.

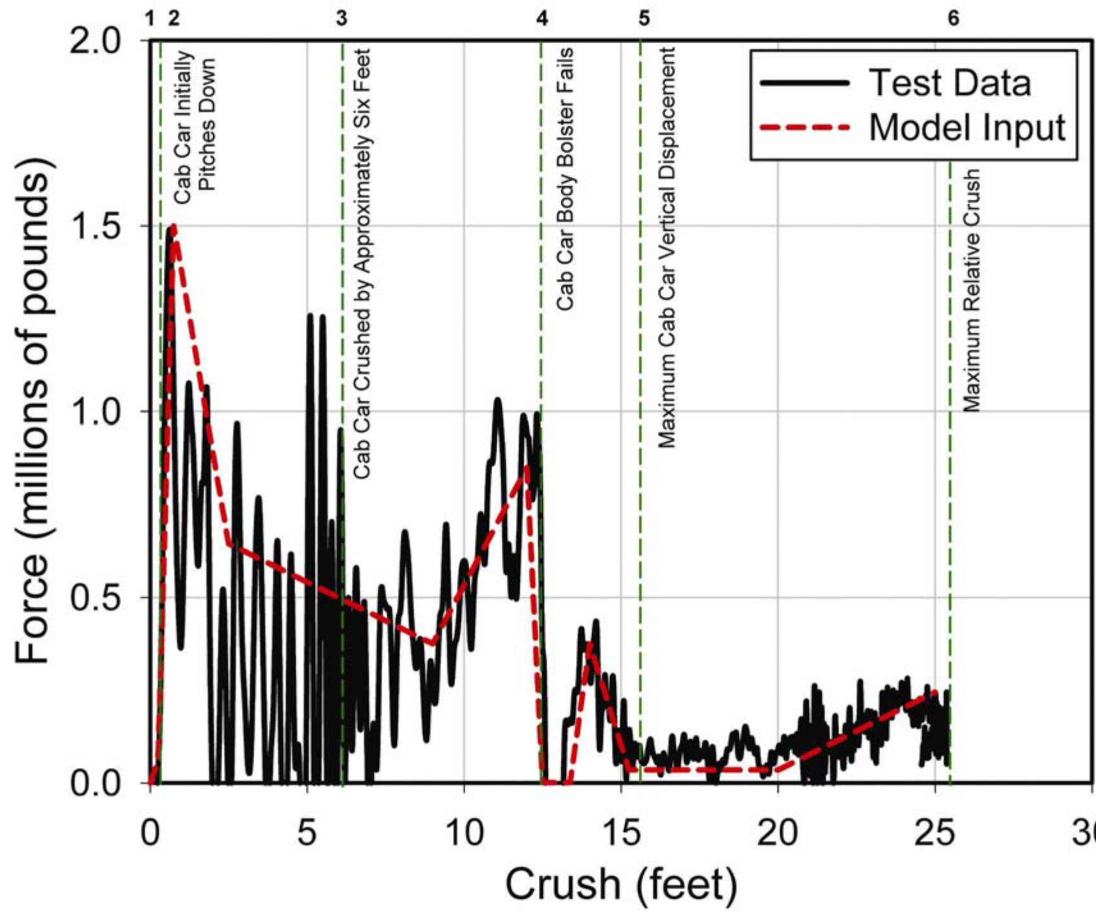

Figure C-3. Cab Car/Locomotive Force/Crush Characteristic

The graph in figure C-3 is annotated with six events that occurred during the interaction of the colliding cab car and locomotive. Photographs of these events, taken from the high-speed film, are shown in Figure C-4:

1. Initial contact, between the couplers of the cab car and locomotive
2. Cab car initially pitches down a small amount up to when the maximum force is reached. Shortly after, the carbody starts to pitch up as the crush continues. Similar behavior was observed in the single car and two-car impact tests [14, 17].
3. Cab car is crushed approximately six feet, about the same amount of crush as in single-car and two-car tests [14, 17]. The carbody is pitched upward in this photograph.
4. Cab car body bolster fails and the front end of the carbody folds downward.
5. Maximum cab car vertical displacement
6. Maximum relative longitudinal displacement of the cab car and locomotive, and maximum crush of the cab car and locomotive.


1. Initial contact


2. Cab car initially pitches down


3. Cab Car crushed approximately same amount as in single-car and two-car impact tests


4. Cab car body folds downward

5. Maximum vertical displacement of cab car

6. Maximum crush

Figure C-4. Photographs from High-Speed Film

C.2 ONE-DIMENSIONAL MODEL PREDICTIONS

Results from the train collision dynamics models include the displacement, velocity, and acceleration time-histories of all the cars. For the one-dimensional model, these results are all for the longitudinal direction. The three-dimensional model results also include vertical and lateral motions, as well as pitch, roll, and yaw motions. The results included in this appendix include the time history of the force acting between the colliding cab car and locomotive, calculated from the longitudinal decelerations of the cars in the cab car led consist, the time history of the relative displacement between the cab car and the locomotive, and the longitudinal decelerations of all the cars and locomotives in both trains. The results from the three-dimensional model, including the vertical/pitch motions and lateral/yaw motions of the cab car, are discussed in the main report.

C.2.1 FORCE

Figure C-5 shows the time history for the force acting between the cab car and the locomotive during the impact. The plot is for the first two seconds after impact, a duration sufficient to include the maximum relative longitudinal displacement of the cab car and locomotive, i.e., the maximum crush. The plot is annotated with the same six events as the force-crush plot shown in Figure C-3. Photographs of these six events are shown in Figure C-4. Figure C-5 shows that the model predictions are in agreement with the test measurements for all the key features of the force-time history, for both the one-dimensional and two-dimensional models. The models do not include elements for the high-frequencies seen in the test data. These high-frequency components do not significantly influence the car motions.

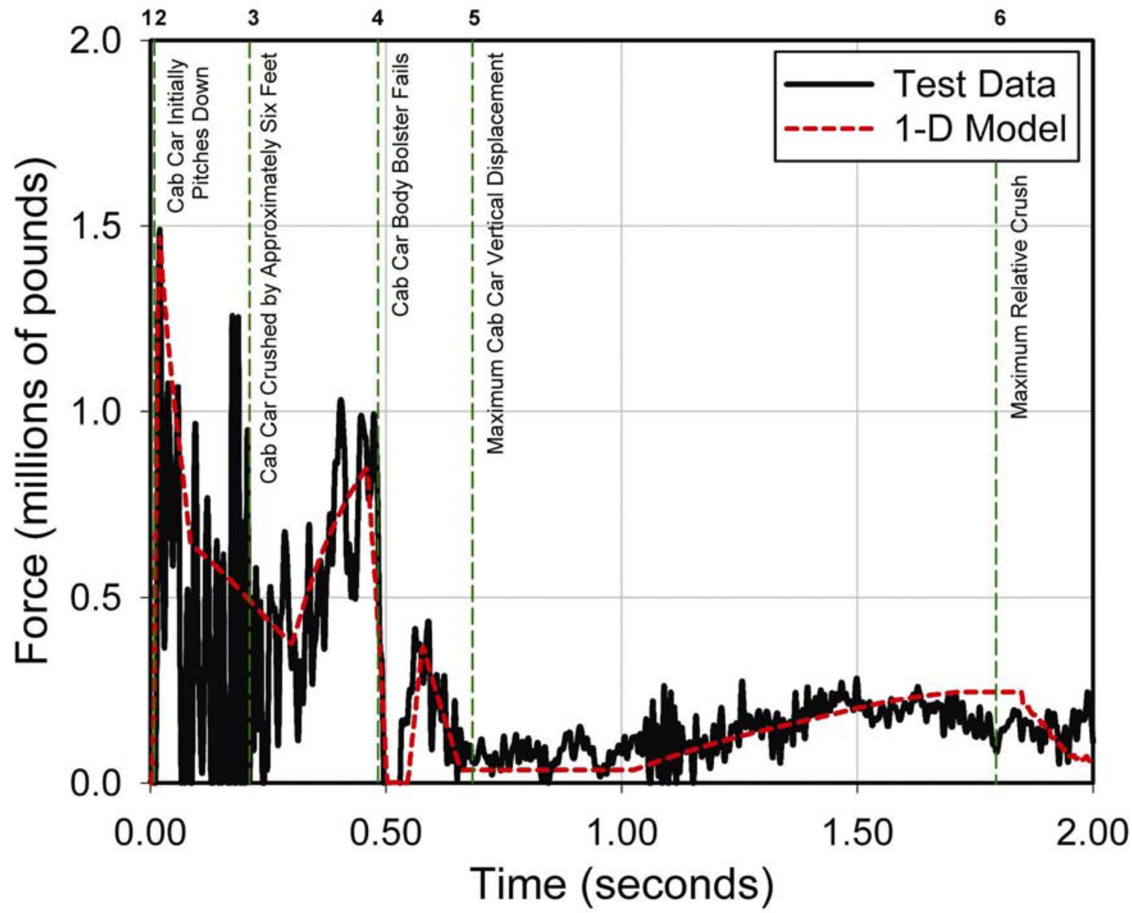

Figure C-5. Cab Car/Locomotive Force-Time History, from Test Data and One-Dimensional Train Collision Dynamics Model

C.2.2 CRUSH

Figure C-6 shows the time history of the relative displacement of the colliding cab car and the locomotive, from the test measurements and as predicted with the models. This relative displacement is the 'overlap' between the colliding cab car and locomotive, and includes the crush of the cab car, the crush of the locomotive, and any longitudinal sliding of the cab car and locomotive relative to each other. The total crush of the cab car was measured as 22.75 feet after the test. The cab car slid relative to the locomotive approximately 2.25 feet when it overrode the short hood of the locomotive, before it impacted the windshield of the locomotive. The centerpost of the windshield crushed approximately 0.75 feet during the impact. The maximum total crush between the cab car and locomotive was approximately 25.75 feet. The figure shows that both models are in close agreement with the test measurements for the relative displacement between the cab car and the locomotive.

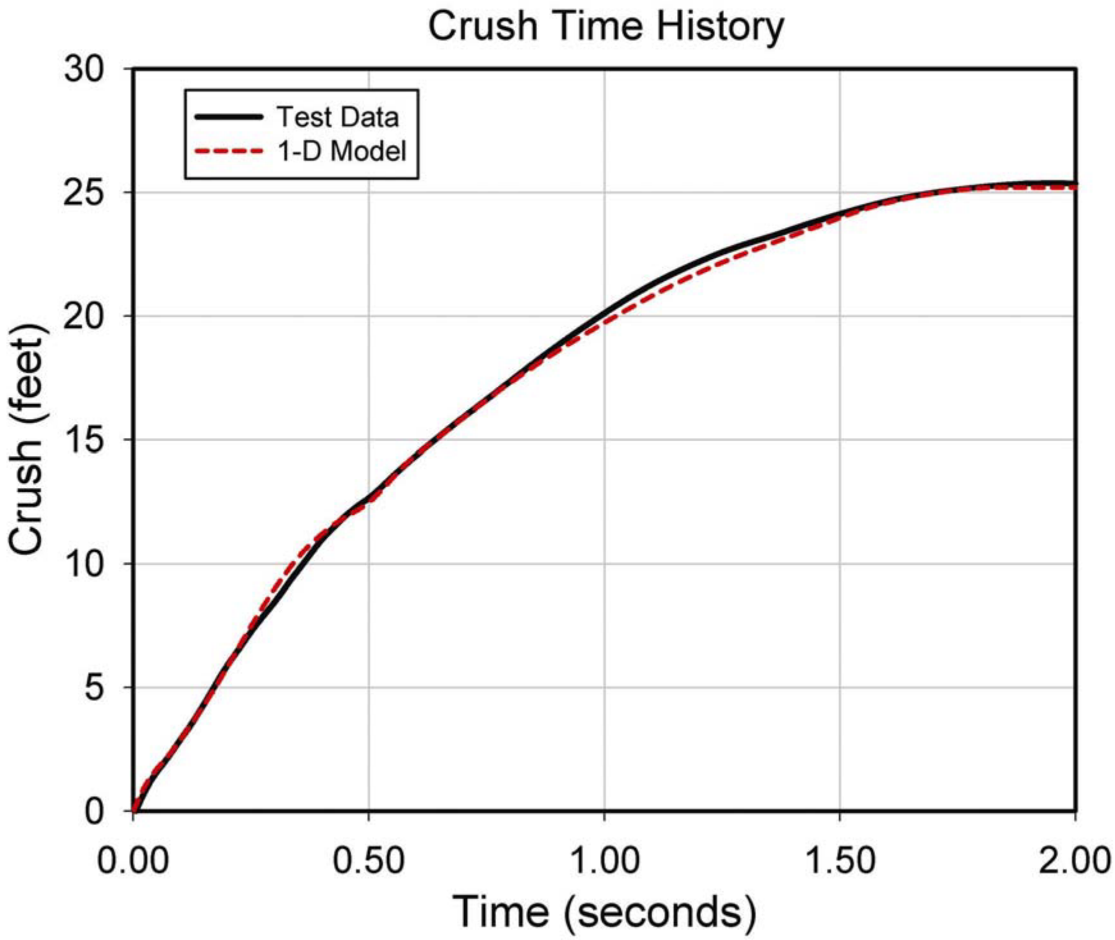

Figure C-6. Cab Car/Locomotive Crush-Time History, from Test Data and Simulation Models

C.2.3 LONGITUDINAL ACCELERATION

Figures C-7 through C-14 show plots of the longitudinal acceleration time histories for all the cars and locomotives in the two consists, both test measurements and model predictions. These figures proceed from the trailing freight car through to the impacted locomotive, and from the impacted cab car to the trailing locomotive, i.e., the plots are in the same order as the cars in Figure C-1.

In general, there is close agreement between the model predictions and test measurements for the acceleration time-histories of all the cars. The measured decelerations of the freight cars and the impacted locomotive all have a visible high-frequency component. Inspection of this locomotive after the test showed that some of the motor/generator mounts were missing critical bolts; it appears likely that the high-frequency component was due to the motor/generator vibrating on a reduced number of mounts. In Figure C-10, the longitudinal deceleration of the cab car, a difference can be seen in the timing and form of the peaks that occur after the first positive and negative peak. Most of these peaks are due to the compression of the draft gear and the impact between buffer beams of coupled cars. In the one-dimensional model, the draft gear is represented by essentially linear elements. The test data indicates that there is substantial friction in the draft gear. The negative peak at approximately 0.5 seconds shown in Figure C-10 is due to a sudden reduction of the force/crush characteristic. The force/crush characteristic briefly goes to zero at just over 12 feet of crush, as shown in Figure C-3, which corresponds to 0.5 seconds after the start of the impact, as shown in Figure C-5.

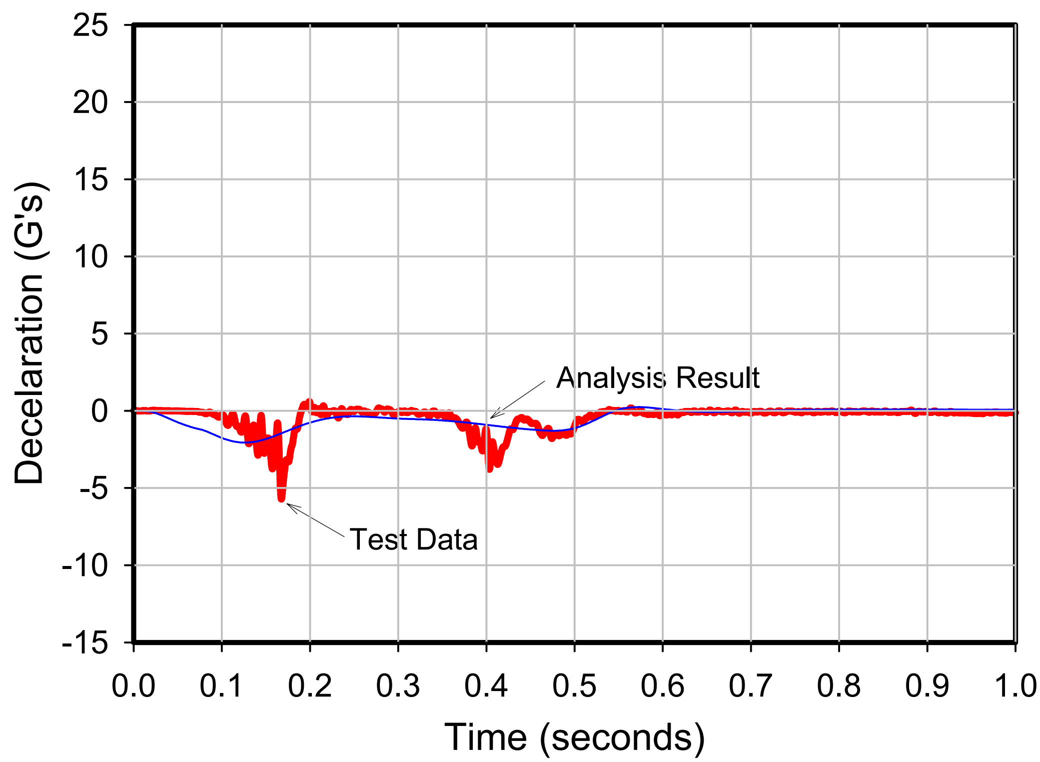

Figure C-7. Longitudinal Deceleration Time-History of Second Freight Car, Test Measurement, Single-Dimensional Model, and Three-Dimensional Model Predictions

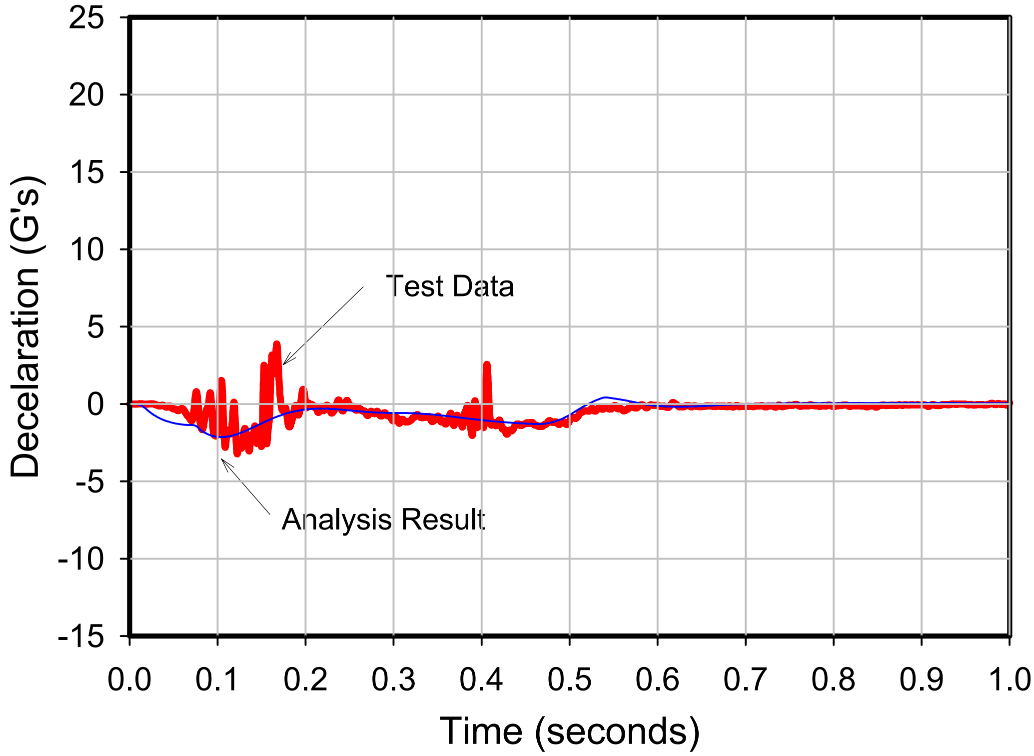

Figure C-8. Longitudinal Deceleration Time-History of First Freight Car, Test Measurement, Single-Dimensional Model, and Three-Dimensional Model Predictions

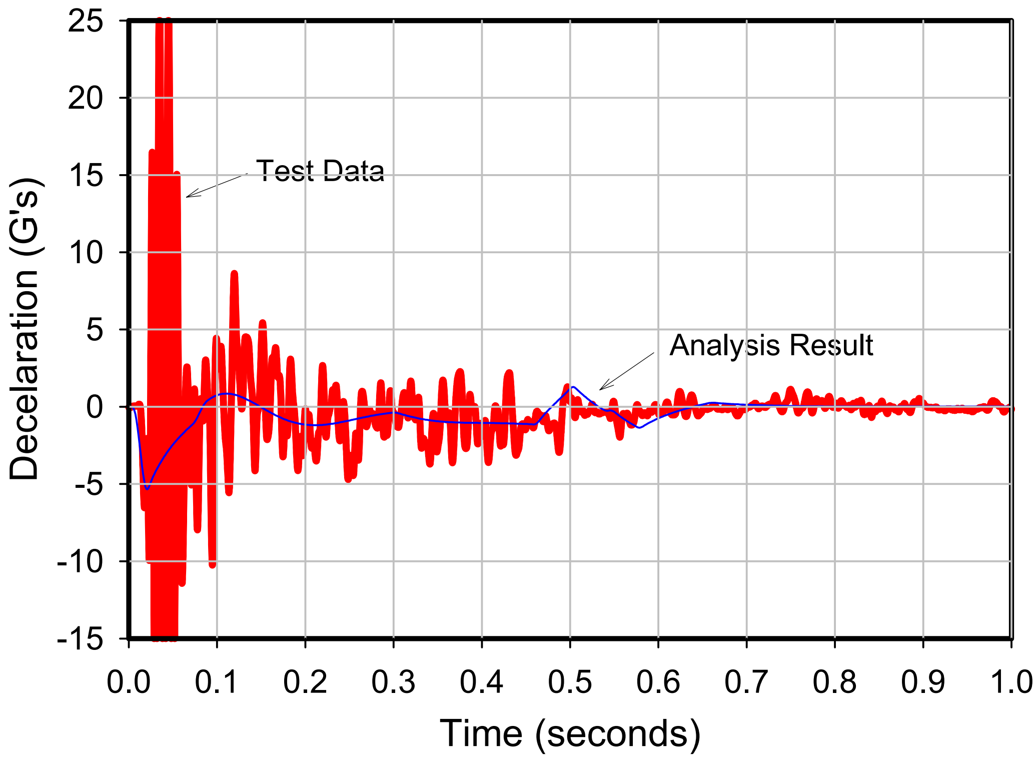

Figure C-9. Longitudinal Deceleration Time-History of Standing Locomotive, Test Measurement, Single-Dimensional Model, and Three-Dimensional Model Predictions

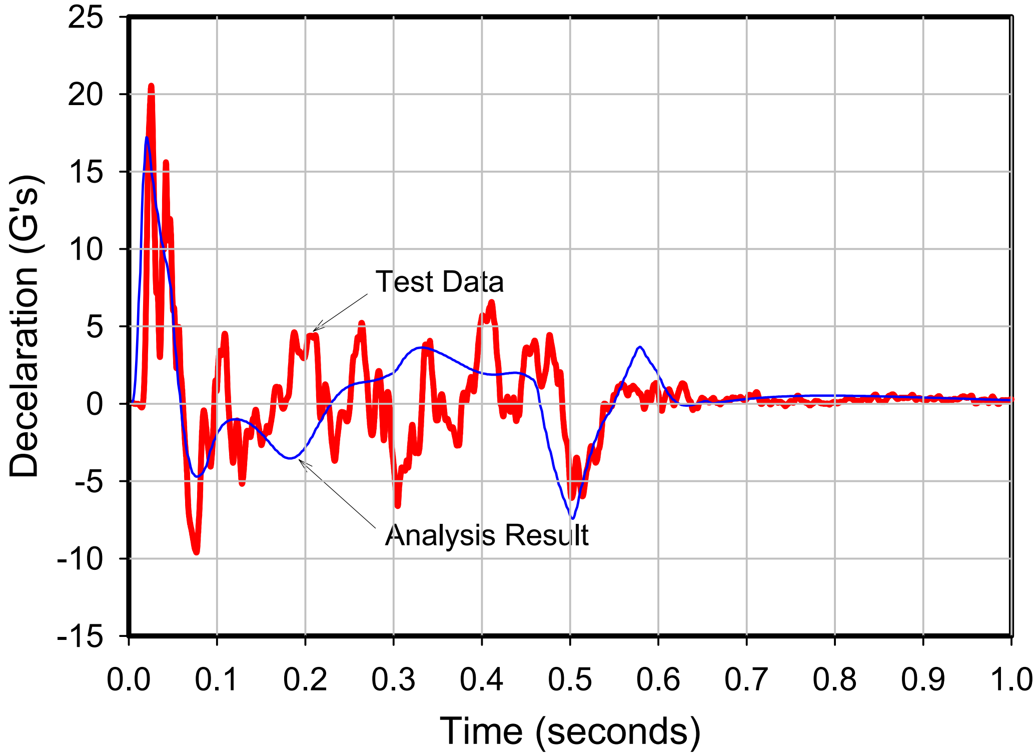

Figure C-10. Longitudinal Deceleration Time-History of Cab Car, Test Measurement, Single-Dimensional Model, and Three-Dimensional Model Predictions

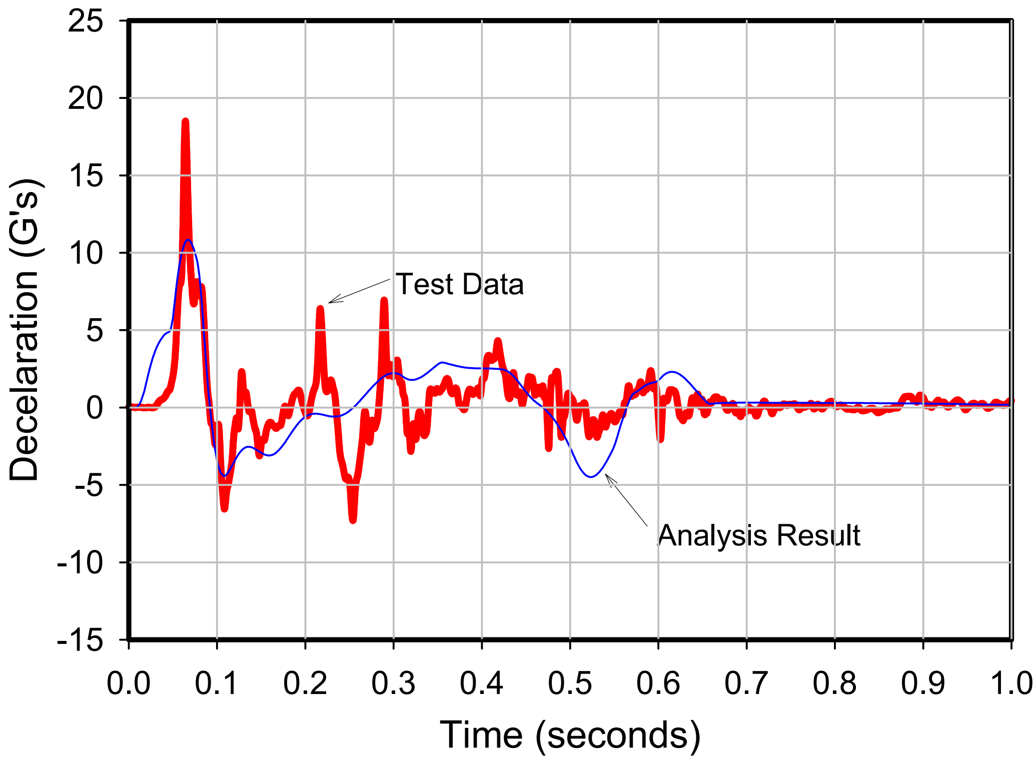

Figure C-11. Longitudinal Deceleration Time-History of First Coach Car, Test Measurement, Single-Dimensional Model, and Three-Dimensional Model Predictions

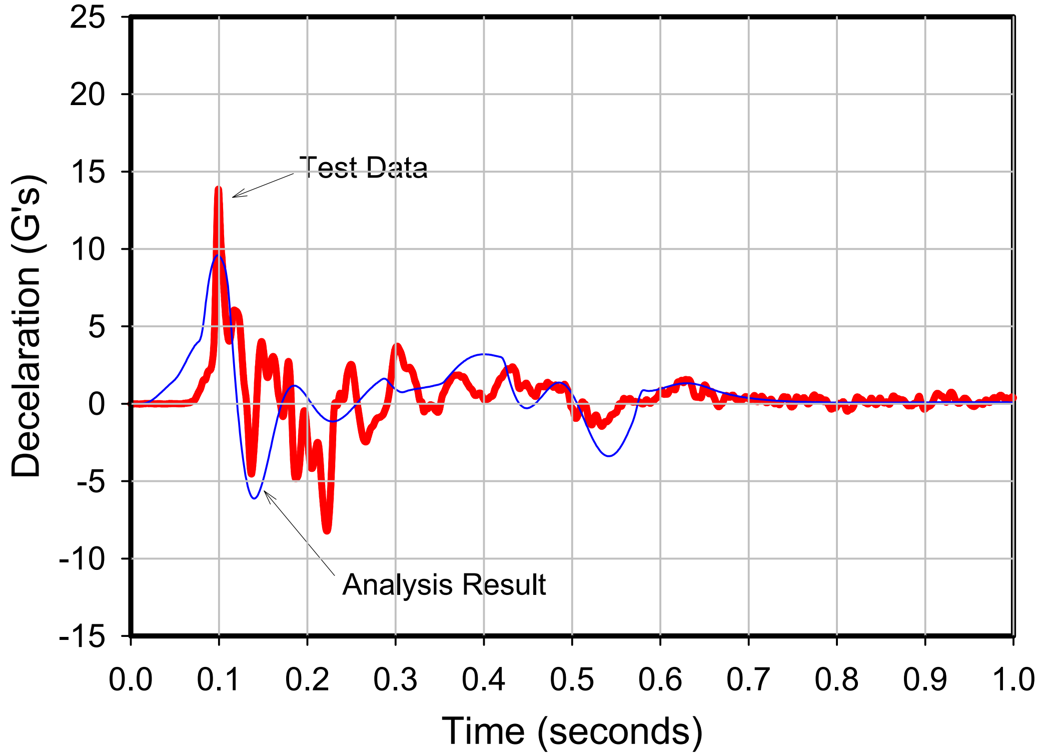

Figure C-12. Longitudinal Deceleration Time-History of Second Coach Car, Test Measurement, Single-Dimensional Model, and Three-Dimensional Model Predictions

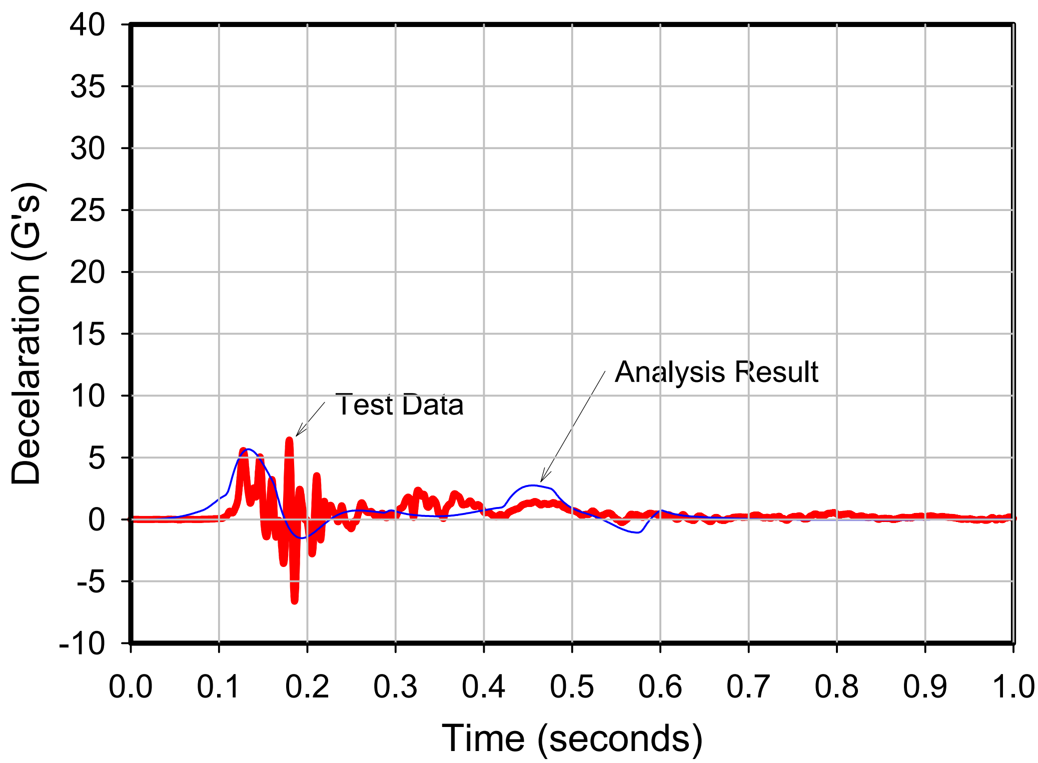

Figure C-13. Longitudinal Deceleration Time-History of Third Coach Car, Test Measurement, Single-Dimensional Model, and Three-Dimensional Model Predictions

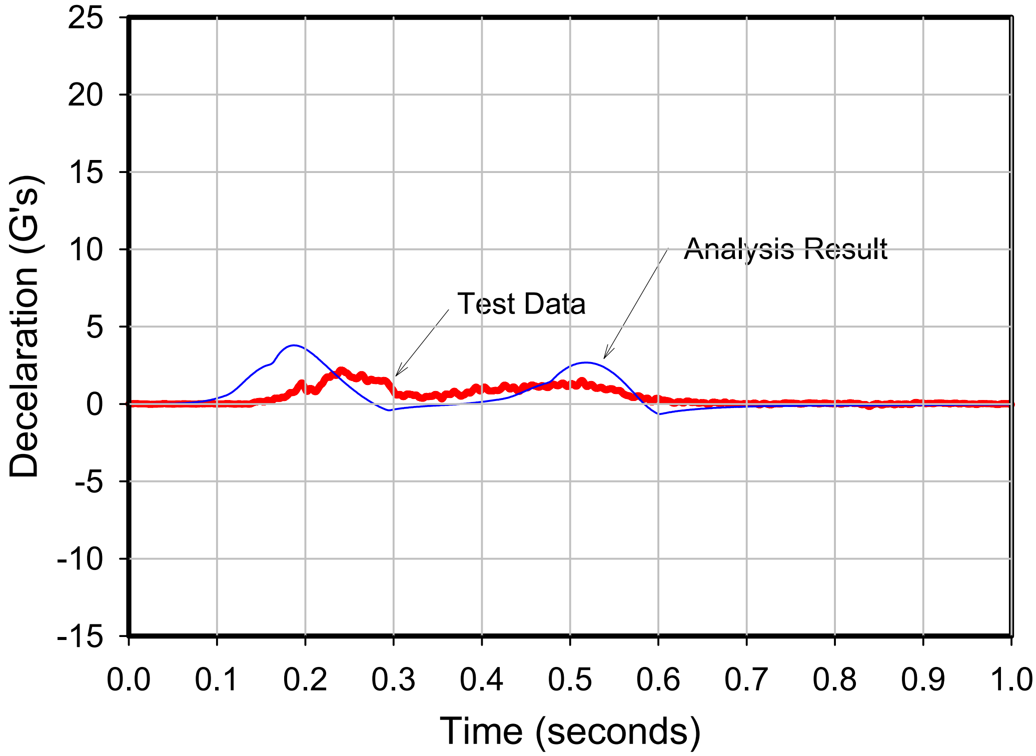

Figure C-14. Longitudinal Deceleration Time-History of Trailing Locomotive, Test Measurement, Single-Dimensional Model, and Three-Dimensional Model Predictions

C.3 CONCLUSIONS

The collision dynamics models are able to capture the fundamental behavior of the trains during the impact. The one-dimensional model represents each car as a single mass, and uses the same force/crush characteristic between all cars, and is able to accurately calculate the crush of the cab car. This model also captures many of the features of the longitudinal decelerations of the cab car and other equipment. A more refined representation of the draft gear is needed in order to capture more accurately some of the secondary features of the longitudinal accelerations of the cars.