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## TRAIN-TO-TRAIN IMPACT TEST: ANALYSIS OF STRUCTURAL MEASUREMENTS

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## ABSTRACT
This paper describes the results of the train-to-train impact test conducted at the 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.

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. The measured response of the trains compare closely with predictions made with simulation models.

## INTRODUCTION AND BACKGROUND

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 that could improve performance. 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 experience 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.

### In-Line Tests of Conventional Equipment

The train-to-train test was conducted as one of three tests to define the performance of conventional rail passenger equipment in an in-line train collision. This test is based on a collision scenario in which a cab car-led train collides with a locomotive-led train, which is illustrated schematically in Figure 1. Examples of such collisions include the Prides Crossing, Massachusetts collision between a commuter train and a freight train [9], the Silver Spring, Maryland collision between a commuter train and an intercity passenger train [10], and the Placentia, California collision between a commuter train and a freight train [11].

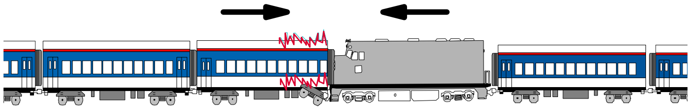

Figure 1. Schematic of In-Line Collision Scenario

The overall objective of the fullscale 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 and models, and to ensure that the factors influencing the response of the equipment and test dummies are taken into account.

The single-car test [12, 13, 14], the two-car tests [15, 16, 17], and the train-to-train test were conducted to define the performance of conventional equipment in the in-line collision scenario. Figure 2 shows schematics of the single-car test, the two-car test, and the train-to-train test. The in-line tests were organized in order of increasing complexity, both in terms of the tests themselves and in terms of the information gathered. The objectives of the single-car test were to measure the force/crush characteristic, to observe the failure modes of the major structural components, and to measure the gross motions of the car. 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. The test requirements for the in-line tests are described in reference [18].

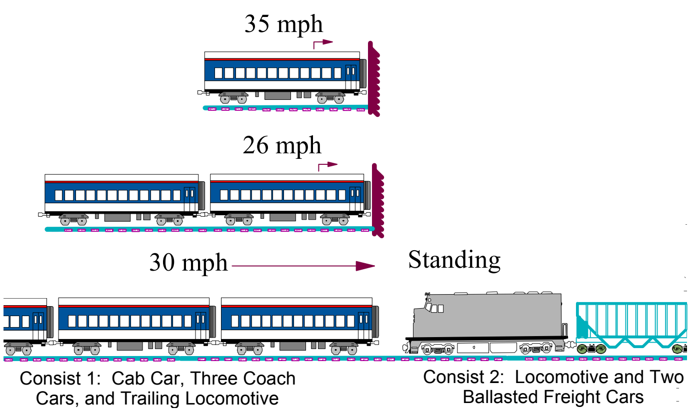


Figure 2. Schematic of Single Car, Two Car, and Train-to-Train Tests

## Occupant Protection Experiments

Figure 3 shows schematics of the occupant-protection experiments included as part of the single-car, two-car, and train-to-train tests. 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 also tested in the first coach car; and the operator's interior in the impacted locomotive. The results of the occupant protection experiments conducted as part of the train-to-train test are described in a companion paper [19]. Forward facing commuter passenger seats, rear-facing commuter passenger seats, and forward facing inter-city passenger seats with lap and shoulder belts were tested in the single-car test and in the leading car in the two-car test. The forward-facing commuter passenger seats were also tested in the trailing car in the two-car test. Test dummies were used in all the occupant protection experiments. The objective of these experiments is to observe the kinematics of the test dummy in several interior configurations, as well as to measure the test-dummy response and evaluate the potential for occupant injury.

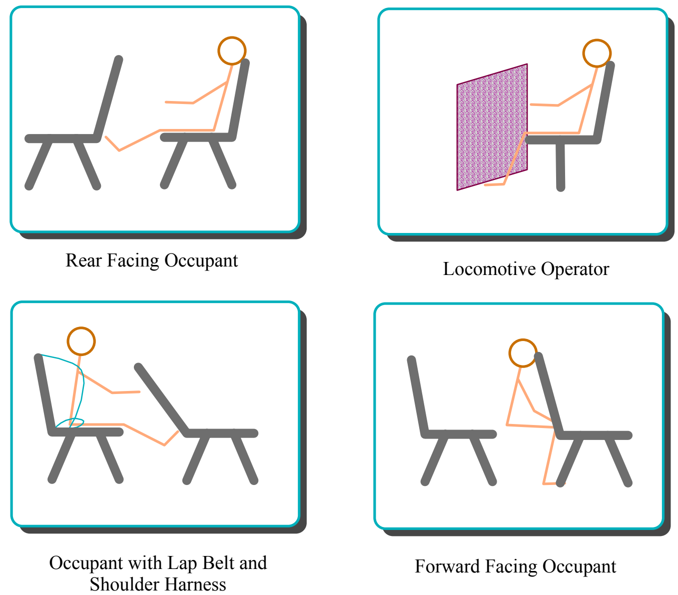


Figure 3. Schematics of Occupant Protection Experiments Included as Part of Fullscale Tests

## Summary of All Fullscale Tests

In addition to the in-line tests, tests based on a grade-crossing collision scenario have also been conducted. The grade-crossing collision tests are intended to measure the effectiveness of the car end structure in preventing intrusion during a grade-crossing collision.

Plans have been made to test improved-crashworthiness equipment in the three tests shown in Figure 2. There was a substantial loss of occupant volume in the cab car in the train-to-train test. It is expected that the entire occupant volume can be preserved under the same test conditions by equipment incorporating crush-zones at the ends [20].

The conditions and the sequence of the tests are listed in Table 1. The first 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 four tests. This arrangement of the tests allows comparison of the conventional-equipment performance with the performance of improved-crashworthiness equipment.

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 crushable end structures, in the tests based on the in-line collision scenario is planned to start in the spring of 2003.

The results of the single-car test and two-car test are summarized in Appendix A. They foretell many of the results of the train-to-train test.

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 | November 16, 1999 | Test 6 |
| Two-coupled-car impact with fixed barrier | April 4, 2000 | Test 7 |
| Cab car-led train impact with locomotive-led train | January 31, 2002 | Test 8 |
| Single-car impact with steel coil | June 4, 2002 | June 7, 2002 |

## TRAIN-TO-TRAIN TEST

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 such that it would cause substantial damage to conventional equipment, with resulting loss of occupant volume, yet be survivable with equipment incorporating an alternative crashworthiness strategy [20]. A more detailed description of the equipment used in the train-to-train test is included in the Appendix B.

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.

### Train-to-Train Test Results

The principal results of the train-to-train test include the loss of occupant volume, the mode of structural deformation and the interaction of the colliding equipment. During the test, the colliding cab car overrode the locomotive. The cab car sustained approximately 22 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 colliding locomotive, with 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 4 shows the interaction of the colliding cab car and locomotive in a series of frames taken from high-speed video recorded during the test.

The entire duration of the test, from initial impact until both trains stopped, was ~9.6 seconds. Immediately after the initial impact, the cab car led train began to slow down, while the locomotive-led train began to move. After ~0.2 seconds, the underframe of the cab car had crushed by ~6 feet, about the same as the maximum cab car crush observed in the single-car and two-car tests [12, 15]. After ~0.3 seconds, both axles of the lead truck of the cab car were off the track, and after ~0.5 seconds the lead truck separated from the cab car. The cab car underframe overrode the locomotive short hood and impacted the window structure of the locomotive after ~0.7 seconds, and finally rode up onto the roof of the locomotive cab after ~1 second. By ~1.2 seconds, the cab car underframe had crushed by ~22 feet. Eventually, just more than ~2 seconds after initial contact of the cab car and locomotive, both trains were moving at the same speed, ~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. Both trains came to a stop~9.6 seconds after the initial impact. The last frame of Figure 4 shows the cab car at approximately ~1.2 seconds, the time of maximum override.

Figure 4. Override of Locomotive by Cab Car, Observed in Train-to-Train Test

Figure 5 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 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. All of the connections of the freight train 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.

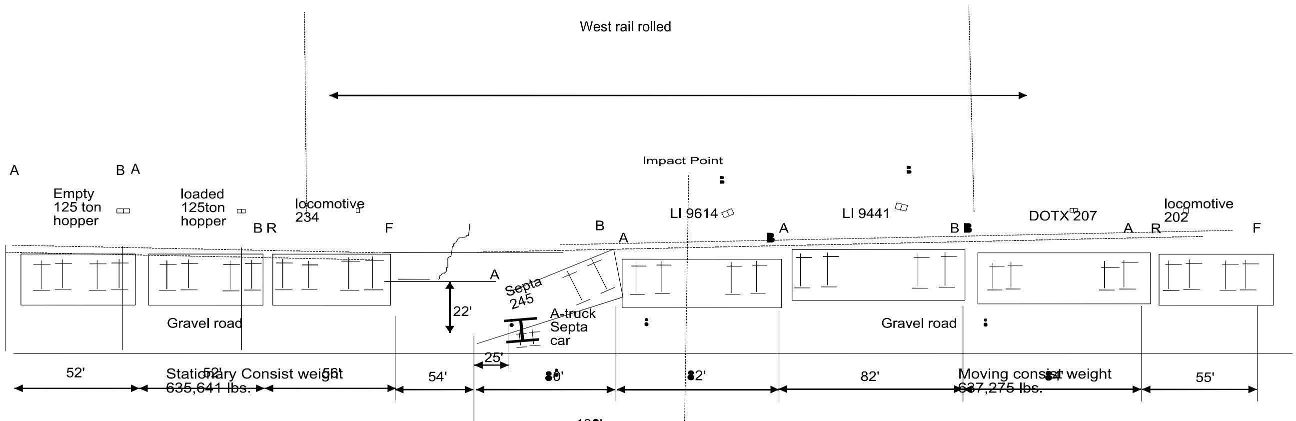


Figure 5. Sketch of Car Positions After Test

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, and after 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 6 shows the cab car led consist immediately after the test.

Figure 6. Cab Car-led Consist from Train-to-Train Test, After Test

During the test, the space for the operator's seat and for approximately ten rows of passenger seats was lost. In total, seating for approximately 47 passengers and one crew was crushed during the test. Figure 7 shows a view of the crushed end of the cab car from the interior. The floor pushed upward, owing to the end crush of the cab car; interior wall and roof panels broke 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 7. Interior of Cab Car, Looking Toward Crushed End

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. The windshield panes each remained as a single sheet, but were heavily crazed with substantial amounts of spall. The conductor's side pane was pushed into the cab by a portion of the cab car roof. The roof was dented above the center pillar of the windshield. Figure 8 shows the short hood end of the impacted locomotive after the test.

Figure 8. Impacted Locomotive, After Test

Damage was focused on the cab car because there was not sufficient force to cause any of the trailing equipment to crush and because 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 sufficiently crushed to have passed its peak force, as shown in Figure A-1 in Appendix A. 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.

## ANALYSIS OF TRAIN-TO-TRAIN TEST MEASUREMENTS

A series of analyses techniques has been used to evaluate the test measurements. These 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 momenta 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 displacements of the cars 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 momenta values provide indications of 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% 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 influences 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 third coach car were developed from available information [21, 22].

### 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 the kinetic energy and momentum of the initially moving, cab car-led consist. Each train was assumed to act as a single body, and the impact was assumed to be perfectly plastic. The influence of braking during the impact and the elastic rebound of the carbodies were neglected. 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 2. Initial Kinetic, Crush, Braking, and Overrride Energies

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

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

### Train Longitudinal Motions

Table 3 compares the amount of underframe crush the cab car sustained in the test with estimates from one- and three-dimensional models. The one-dimensional model slightly overestimates the crush because the energy went into override in the test is dissipated as crush in this model. Since the amount of energy associated with override is small, the associated error is also small. The three-dimensional model closely predicts the amount of crush observed in the test, but under-estimates it slightly.

Table 3. Cab Car Crush Measured in Test and Predicted with One- and Three-Dimensional Models

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

Figure 9 compares the measured deceleration time-history of the cab car, for the first second of the impact with the predictions from the one- 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 seconds, 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 of the models. As a result, after 0.2 seconds the model predictions and test results are out of phase; otherwise there is close agreement between the models and the test data.

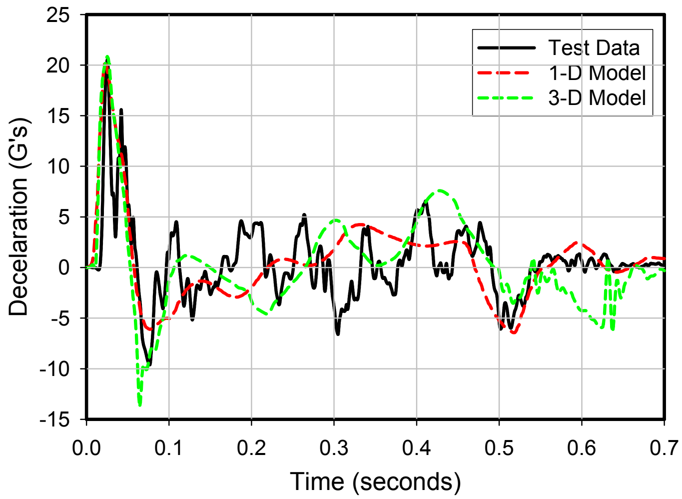


Figure 9. Longitudinal Deceleration Time-History of Cab Car, Test Measurement, Single-Dimensional Model, and Three-Dimensional Model Predictions

## Colliding Equipment Interaction

Figure 10 shows the range of possible interactions between the colliding cab car and locomotive:

1. The cab car overrides the locomotive,
2. The locomotive overrides the cab car,
3. The cab car and locomotive deflect past each other, and
4. The cab car and locomotive remain engaged.

In the test the cab car overrode the locomotive and deflected laterally. This override was apparently due to the cab car in the train-to-train test initially crushing in a manner similar to the vehicles in the single-car, and two-car tests [12, 15, 23]. In all three tests the cab car underframe essentially formed a ramp as it crushed. 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 large enough to overcome the weight of the cab car, and continue its upward pitch, allowing the cab car to override the locomotive.

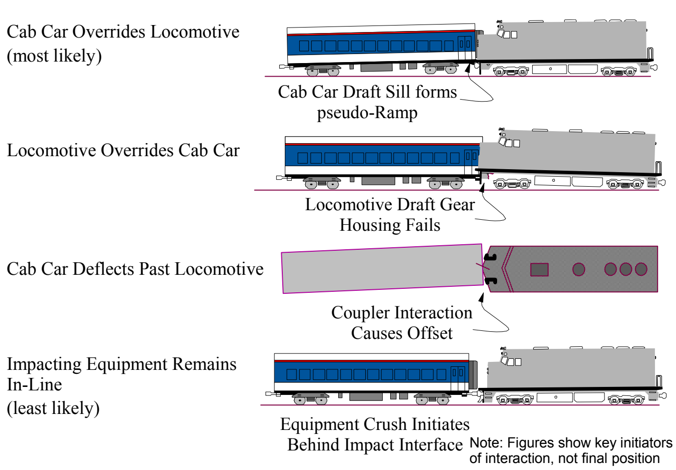


Figure 10. Potential Modes of Colliding Equipment Interaction

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 lateral 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 [24] – approximately 3000 kips -- is close to the load required to initiate crush of the cab car underframe – 2750 kips. If the load required to shear the locomotive's draft gear housing had been somewhat lower than estimated, then the locomotive could 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 crush initiating behind the impact interface. This situation occurred in the recent locomotive-led freight train collision with a cab car-led commuter train in Placentia, California [11]. (The passenger cars in the accident had significantly different structures than the cars that have been used in the fullscale tests.)

## Train Vertical Motions

The train vertical motions include the override of the locomotive by the cab car, as well as the response of each of the cars on their suspensions. Figure 11 shows the results of the three-dimensional model at a time that corresponds to the picture from the test shown in the last frame of Figure 4. With Figures 4 and 11 side by side, the model results compare closely with the test results.

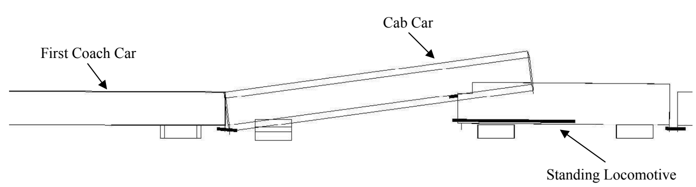


Figure 11. Plan View Schematic(s) of Coupled Car Interaction, Model Results

Figure 12 shows the pitch time-history of cab car as measured during the test and as evaluated with the three-dimensional model. Up to 0.6 seconds there is close agreement between the model predictions and the test measurements. From approximately 0.6 seconds to 0.7 seconds, 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. Refining these elements to more closely represent the geometry of the locomotive should lead to even closer agreement between the model and the test data.

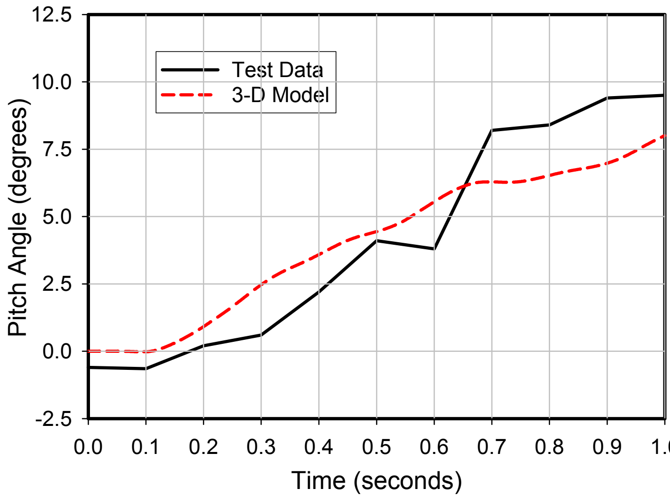


Figure 12. Pitch Time-History of Cab Car, Test Measurement and Three-Dimensional Model Predictions

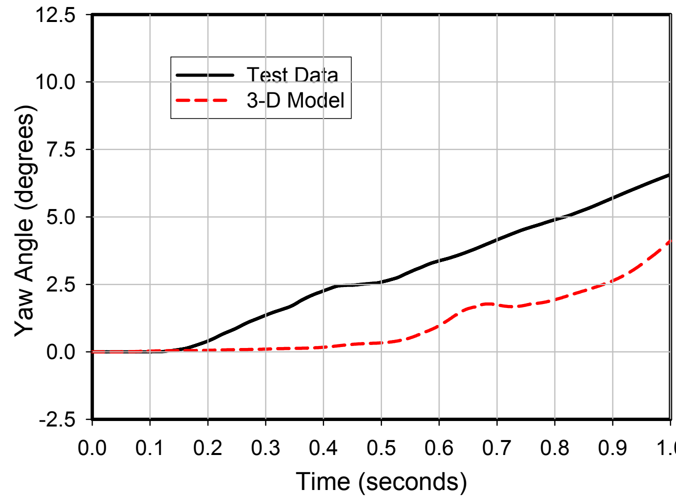


Figure 14. Yaw Time-History of Cab Car, Test Measurement and Three-Dimensional Model Predictions

## 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 car's lateral displacement occurred when the two trains separated, and the cab car rolled as it slid off the locomotive. Figure 13 shows a schematic of the model results for the cab car at maximum lateral displacement (and at maximum override) at approximately 1 second after the impact. The mode of lateral train buckling predicted by the model is similar to the mode observed in the test. For comparison, Figure 5 shows the configuration of the train after the test; note that Figures 5 and 13 are for different times after the initial impact.

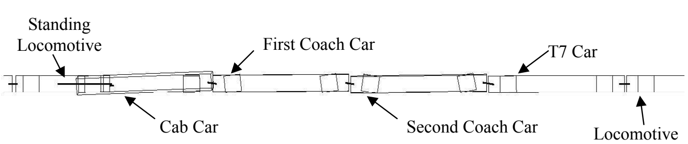


Figure 13. Elevation View Schematic Train Buckling, Model Results

Figure 14 shows the yaw time-history of 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.

## SUMMARY AND DISCUSSION

The train-to-train test was the third in a series of tests intended to define the performance of current-design equipment in in-line collisions. In the first test, a single passenger car impacted a fixed barrier to provide measurements of the force required to cause significant crush of the car and to observe the geometry of the crushed structure. In the second test, two-coupled passenger cars impacted a fixed barrier. The principal incremental objective was measurement of 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 additional objectives of the train-train-test were observation of the interaction of the colliding equipment, measurement of the occupant environments, and measurement of 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. 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 measurements have been completed. Analysis predictions of the crush and decelerations of the cars and compare closely with test measurements. The structural measurements are currently being used to refine simulation models.

Preparations are underway for testing crash energy management design equipment. A corresponding series of single car, two car, and train-to-train tests are planned for crash energy management (CEM) equipment. For the train-to-train test of the CEM equipment it is anticipated that the car crush will be distributed among the ends of all of the cars. As a result, there should be no intrusion into the occupant volume for the passengers. 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 potential loss of volume for the operator. Means of protecting the operator, such as a cage that is pushed back into a utility closet in the event of a collision, are being investigated.

Fullscale tests based on a grade-crossing collision with a heavy rigid object have also been pert of this research effort. 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. The results of these tests, performed on June 4 and June 7, 2002, are currently being processed and will be reported in the near future.

## ACKNOWLEDGEMENTS

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## APPENDIX A -- SELECTED SINGLE-CAR AND TWO-CAR TEST RESULTS

### Single Car Test

Figure A-1 shows the force/crush characteristics developed from measurements made during impact tests of a single passenger car into a fixed barrier [12, 23, 25]. This curve has high initial peak load followed by significantly lower loads, which are approximately constant, for continued crush.

One implication of the force/crush characteristic shown in Figure A-1 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 A-1, 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. The most force the car ahead can exert is the lower crush load, while the car behind requires the peak load in order to start crushing. There is often little damage to the trailing cars in train collisions of typical U.S. passenger rail equipment.

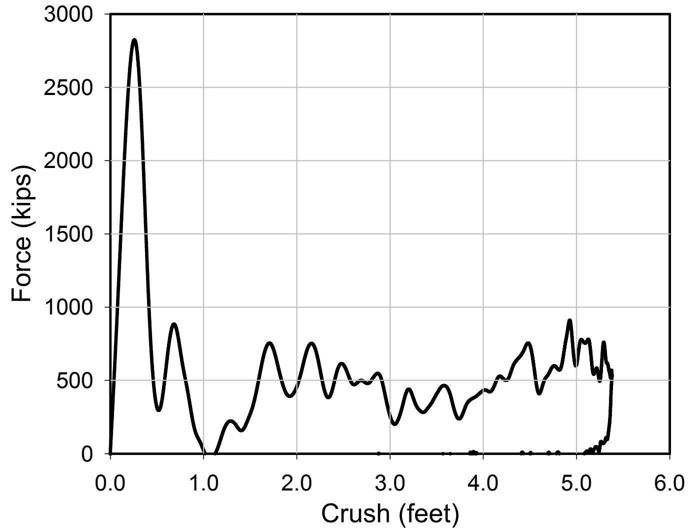


Figure A-1. Force/Crush Characteristic Developed from Single-Car Test Measurements

### Two-Car Test

During the two-car test, the cars remained coupled, but buckled in a saw-tooth mode [15, 25, 26]. 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 rail rolled 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 A-2 shows the coupled connection between the two cars at their final lateral displacement.


Figure A- 2. 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 large-displacement 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, large-displacement buckling, and side-to-side impacts due to large-displacement buckling have been observed in accidents [27, 28]. The progression of the cars from in-line, to the sawtooth lateral buckling pattern, then to the large amplitude pattern has been simulated [4] with computational models.

As expected, the leading end of the lead car sustained significant structural damage – its length was reduced by nearly six feet – 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. This result is a consequence of the force/crush characteristic shown in Figure A-1.

## APPENDIX B -- MAKEUP OF TRAINS IN TRAIN-TO-TRAIN TEST

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 F-40ph. The locomotive-led train was made up of a GM/EMD F-40ph, 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 B-1 shows the initially moving cab car-led train just prior to the test.

Figure B-1. 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 show in Figure B-2. The front skin was attached to the end structure prior to the test.

Figure B-2. Modified Cab Car End Frame

The end structure of the locomotive was modified to comply with the current AAR S-580. 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 B-3 shows the impacting locomotive the test track shortly before the test, along with the two ballasted open-top hopper cars.

Figure B-3. Locomotive-led Consist from Train-to-Train Test, Prior to Impact