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An Overview of Passenger Equipment Full-scale Impact Tests: Results to Date

1 Abstract

As part of the Federal Railroad Administration's Equipment Safety Research Program, a series of full-scale impact tests are being conducted on rail passenger vehicles. Four types of tests are intended to define the performance of current-design equipment in in-line collisions and grade crossing collisions:

In-Line Tests:

1. A single-car impact with a fixed wall
2. A two-car impact with a fixed wall
3. A moving cab-car-led train impact with a standing locomotive-led train

Grade-Crossing Test:

4. A single-car impact with a steel coil

The in-line tests are designed to first measure the crashworthiness of a single car, then the interactions of two cars when coupled, and finally the behavior of a complete train. The grade crossing test is designed to measure the crashworthiness of a single car when a steel coil collides with the corner of the lead end of a cab-car. Conventional and improved-crashworthiness equipment are being tested in all four test conditions.

While the principal objective of the in-line tests is to determine effective strategies for improved structural crashworthiness and improved occupant protection, a secondary objective is to validate and improve the computer models that have been developed as part of the rail vehicle crashworthiness research. These models are used to validate proposed redesigns of components to be used in future tests.

Results from the in-line tests conducted to date show that the force upon impact reaches a high initial peak, and then decreases as the car crushes. The consequence of this decreasing force/crush characteristic is that the structural damage will be focused on the impacting cars in a collision, with very little damage to the trailing cars. Analysis predictions of the crush and decelerations of the cars in the train-to-train test compare closely with test measurements. In the grade-crossing test, the results demonstrated that the improved design standards for corner posts are effective in improving the crashworthiness of cab cars during an impact with a stationary steel coil.

A corresponding series of single car, two car, and train-to-train tests are planned for crash energy management equipment.

2 Introduction

The Federal Railroad Administration's (FRA) Office of Research and Development has been searching for ways to improve crashworthiness in railroad equipment through reviewing relevant accidents and then identifying options for design modifications that could improve performance, and compare the performance of the modified designs to the performance of conventional designs.

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 post-derailment rollover events have been modeled, and the responses of locomotives, cab cars, and coach cars have been simulated in a range of collision scenarios.

A series of tests has been planned to measure the crashworthiness performance of full-scale rail passenger equipment. The overall objective of the full-scale 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. Table 1 shows dates either when each test took place or is scheduled to take place.

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	November 10, 2003
Two-coupled-car impact with fixed barrier	April 4, 2000	December 15, 2003
Cab-car-led train impact with locomotive-led train	January 31, 2002	November, 2004 (tentatively scheduled)
Single-car impact with a steel coil	June 4, 2002	June 7, 2002

Two types of tests are being conducted: In-line train, and grade crossing. Each type follows the same general approach. First, accidents are reviewed to provide information such as characteristics of the collision, and to point to possible ways to reduce damage and injury. Second, design changes are proposed, and computer simulations developed. Third, selected components are built and tested to predict their behavior before they are installed on modified equipment. Fourth, tests are run with modified equipment and the data compared with computer models to correlate the results.

3 In-Line Scenarios

Accidents

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. These tests are based on a collision scenario in which a cab car-led train collides with a locomotive-led train. Examples of such collisions include the Prides Crossing, Massachusetts collision between a commuter train and a freight train [7], the Silver Spring, Maryland collision between a commuter train and an intercity passenger train [8], and the Placentia, California collision between a commuter train and a freight train [9].

In Placentia, California on April 23, 2002, a westbound commuter train came to a complete stop at the Atwood control point. Meanwhile, an eastbound freight train approached on the same track. At approximately 8:10 a.m., a freight train, though in full emergency braking at the time, collided head-on with the passenger train at approximately 22 mph. The passenger train had been traveling in a cab car leading arrangement; where the cab car was the westernmost car in the passenger consist. Consequently, the lead locomotive in the freight consist collided with the cab car in the passenger consist. Out of approximately 265 passengers and crew initially on the passenger train, 161 were transported to local hospitals, and two of the passengers received fatal injuries. The two freight locomotive cab occupants received minor injuries. Figure 1 shows the arrangement of each train after the accident.

Figure 1. Post-accident photographs, lead cab car and lead locomotive, Placentia, California collision

Conventional and CEM Design Strategies

Conventional crashworthiness design strategies were focused on making the individual cars as strong as they can be made, within weight and other design constraints. This approach attempts to control the behavior of individual cars during the collision. Figure 2 shows a schematic illustration of the principal structural members of a conventional single-level passenger rail car. (The underfloor structure of bi-level equipment is similar to single-level equipment at the ends of the car up to and including the structure for attachment of the secondary suspension.) The principal crashworthiness requirement for North American rail passenger equipment since the 1940’s has been the 3.56 MN (800 kip) buff load requirement [10]. The buff load requirement is intended to assure a minimum strength of the occupied volume of the car.

Currently, vehicles intended for operation in the U.S. must be designed according to the Code of Federal Regulations (CFR) [11]. Furthermore, the current practice is to design according to the American Public Transportation Association (APTA) SS-C&S-034-99 Standard for the Design and Construction of Passenger Railroad Rolling Stock [12].

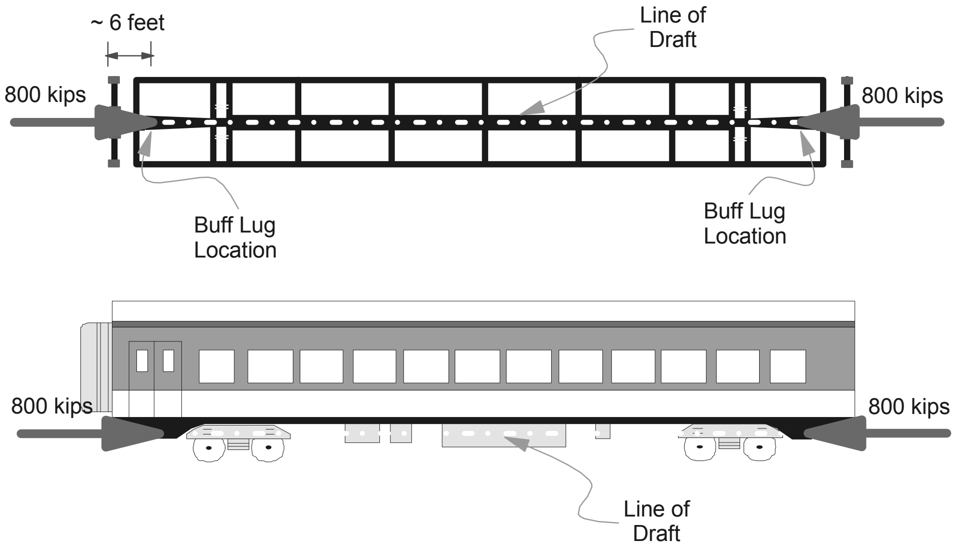

Figure 2. Schematic illustration of a conventional passenger rail car

The crash energy management (CEM) design strategy is focused on apportioning the structural crushing throughout the train to unoccupied areas in order to preserve the occupant volumes and to limit the decelerations of the cars. This strategy attempts to control the behavior of the entire train during the collision. The CEM strategy employs crush zones at the ends of the cars, which are designed to collapse in a controlled fashion during a collision, consequently distributing the crush among the cars of the train [13,14,15,16]. Between the buff lugs, a CEM car can be designed to support the 800 kip buff load, while requiring a lower force to crush the car outboard of the buff stops. In other words, CEM can be incorporated into a car design that is compliant with all current U.S. regulations. Figure 3 shows the location of the crush zones at the ends of each of the cars of the train.

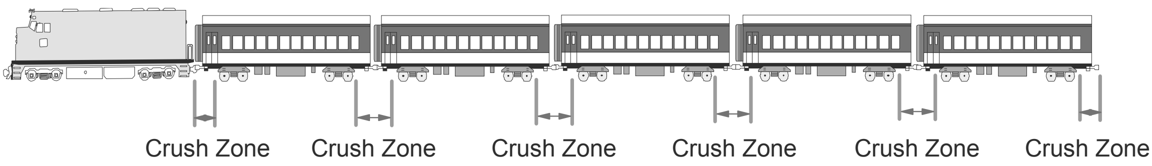

Figure 3. Schematic illustration of crush zone locations in rail passenger train used in push/pull service

In-Line Tests

Three sets of tests were developed, each building in complexity compared to the previous test. Each set has two separate tests, one test using conventional equipment, and one with equipment modified with CEM design components.

The single-car test [17, 18], the two-car test [19, 20] and the train-to-train test [21, 22] were conducted to define the performance of conventional equipment in the in-line collision scenario. Figure 4 shows schematics of each of these tests. The objectives of the single-car test was 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 [23].

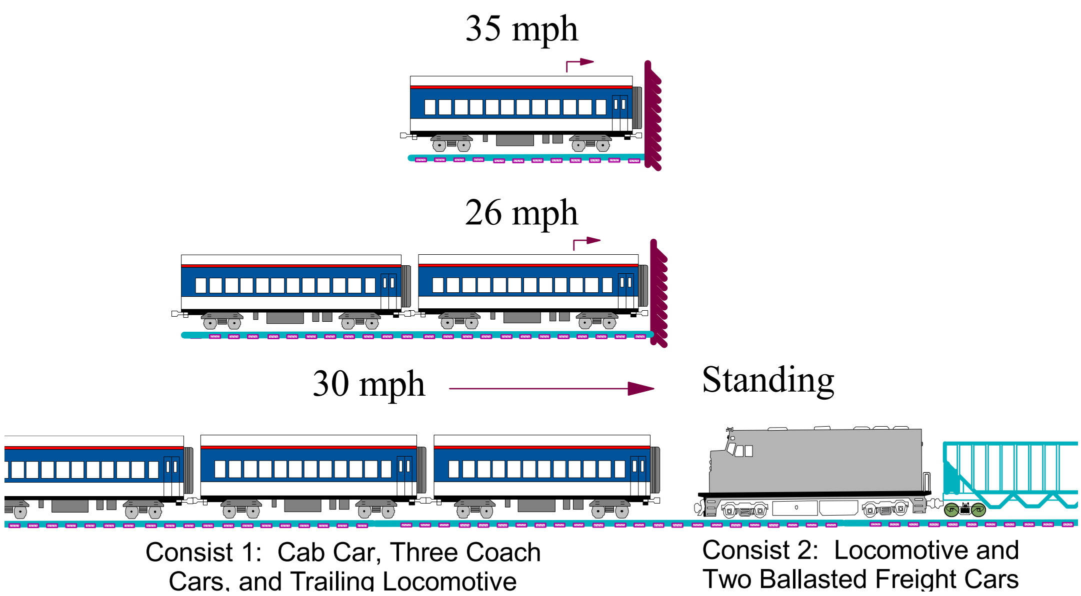

Figure 4. Schematic of the in-line train tests

To date the in-line single-car, two-car, train-to-train tests have been conducted using conventional equipment, while grade crossing tests have been conducted with both conventional and modified equipment. By the end of next year, the remaining tests using CEM designed components will be completed.

Single-Car Test

Figure 5 shows the force/crush characteristics developed from measurements made during impact tests of a single passenger car [17]. This curve have high initial peak loads followed by significantly lower loads, which are approximately constant, for continued crush. Figure 5 also shows the force/crush characteristic predicted for CEM equipment. An increasing force is predicted for just over 3 feet of crush. Crush, as shown in Figure 5, starts with the longitudinal displacement of the coupler into the car immediately after the coupler touches the wall, for both the conventional and CEM curves.

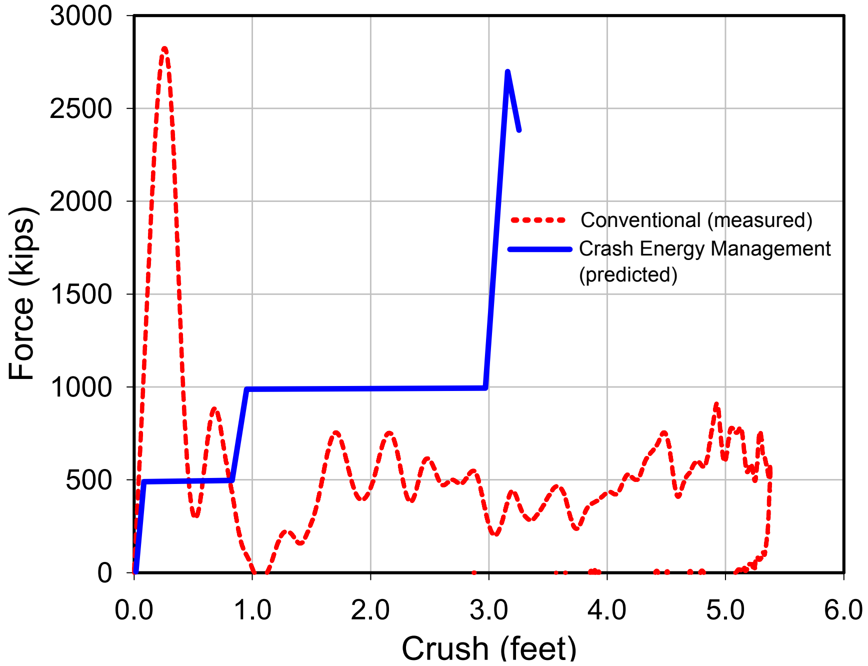

Figure 5. Force/crush curves, typical U.S. passenger equipment

One implication of the force/crush characteristic for conventional equipment, shown in Figure 5, is that the crush will be focused on the colliding cars. Once the impacting car has been crushed by 100 mm (4 inches), the most force it can exert is significantly less than the peak force, while any cars behind can apply up to the peak force. The shape of the characteristic is why, in the test of two coupled cars with a fixed barrier, the lead car sustained significant structural damage 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 implication of the force/crush characteristic shown for CEM equipment in Figure 5 is that the crush will be distributed among the cars of the train. When the impacting car has reached the plateau in the curve where it takes 1000 kips to crush the front of the car, sufficient force can be supported on the trailing end for it to start to its crush at 500 kips.

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 [19]. 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 762 mm (30 inches). The final lateral displacement was 381 mm (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 6 shows the coupled connection between the two cars at their final lateral displacement. This figure also shows a schematic of the predicted relative position of the coupled cars after the two-car impact test of CEM equipment. The CEM equipment is expected to stay in line during this test.

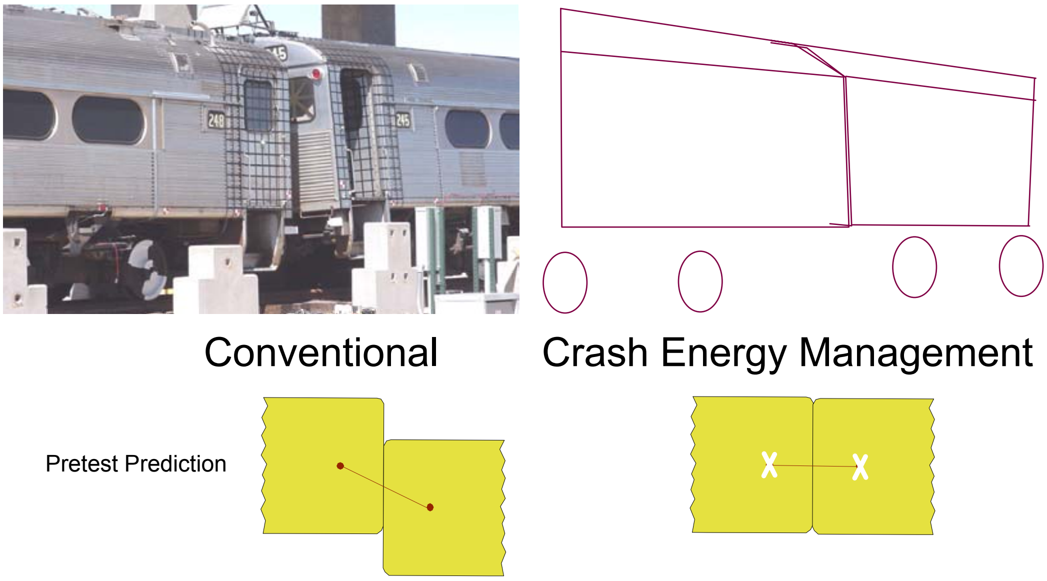

Figure 6. Observed coupler configuration in the conventional in-line test between two cars, and predicted coupler configuration in the CEM in-line test

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 zig-zag 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. The results of this behavior have been observed in accidents [24, 25, 26]. The progression of the cars from in-line, to the sawtooth lateral buckling pattern, then to the zig-zag pattern has also been simulated [27] with computational models. The progression from in-line to sawtooth buckling was observed and measured in detail during the two-car test [19].

Train-to-Train Test

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 [21]. 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. There was substantial loss of occupant volume during the test. Figure 7 shows a series of still photographs taken from a high-speed movies of the test.

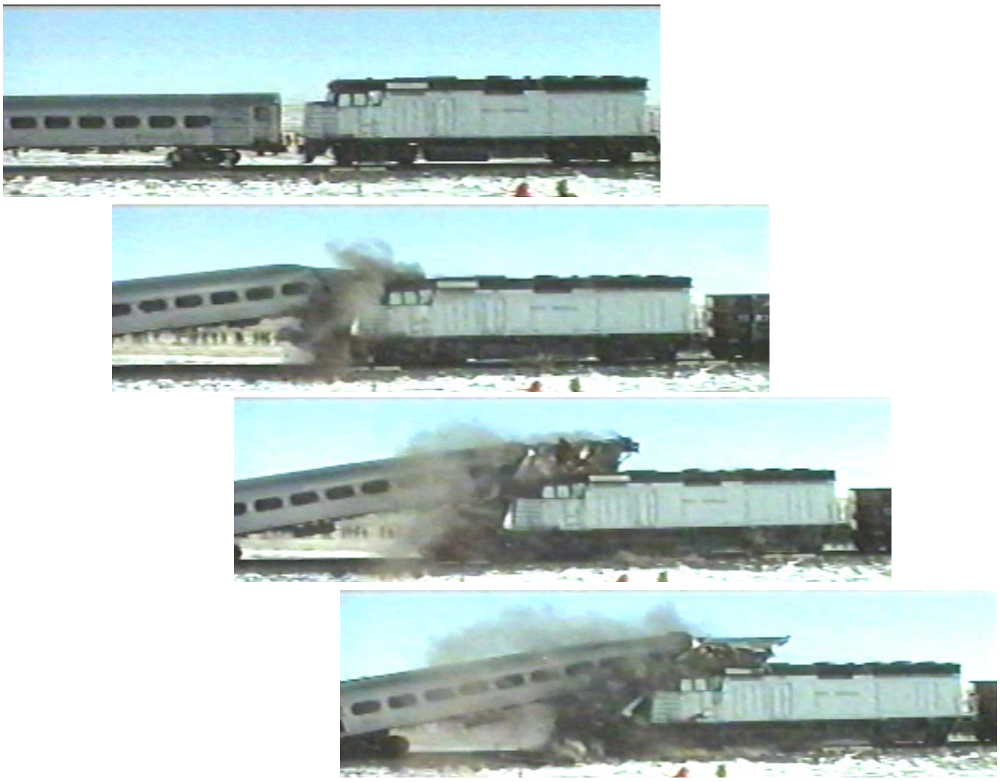

Figure 7. Sequential photos of the in-line train-to-train test

Figure 8 shows preliminary estimates for the train-to-train tests of CEM equipment, with the impact occurring at 30 mph. For the CEM equipment, there is no loss of occupant volume for the passengers and there is no override between the colliding equipment. There potentially is loss of volume for the operator, however means of protecting the operator, such as an operator's cage that gets pushed back in the event of a collision, are being investigated.

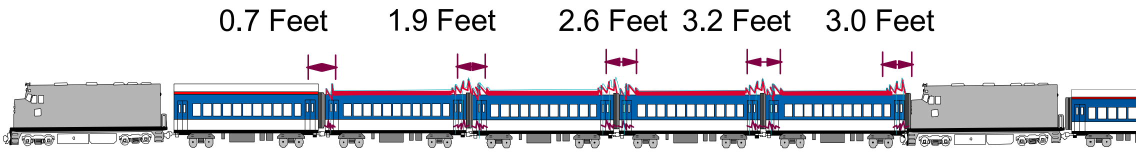

Figure 8. Predicted crush between cars in the cab-car led CEM design train in the in-line train-to-train collision

4 Grade Crossing Tests

Accidents

The grade-crossing tests were conducted to evaluate the crashworthiness of alternative cab car end structure designs. These tests are based on a collision scenario in which a cab car-led train collides with a highway tractor trailer carrying coils of steel at a grade-crossing. Examples of such collisions include the Yardley, Pennsylvania collision between a cab-car-led commuter train and a tractor semi-trailer carrying cols of steel [28] and the Portage, Indiana collision between a cab-car led commuter train and a tractor-tandem trailer carrying coils of steel [29]. In Portage, Indiana on June 18. 1998, a passenger train struck a semi-trailer pulling two flatbeds loaded with steel coils weighing 20 tons each. As the vehicles collided, the cables restraining the coils severed and an impacting coil broke through the end structure and bulkhead of the cab car and proceeded to crush through the passenger compartment. This collision resulted in five minor injuries and three fatalities. Figure 9 shows the cab car, the highway trailer, and the coil of steel after the accident.

Figure 9. Photos of the steel coil used in the grade crossing test, and the crush of the cab car after the collision

State-of-the-Art and Conventional Design Strategies

Two similar tests took place involving a cab car traveling on tangent tracks colliding obliquely into a 41,300 lb steel coil raised about four feet above the top of the rail on a frangible support – the base of the coil located two inches above the substructure [30, 31]. In the event of a grade-crossing collision with a freight truck, heavy objects may potentially challenge the strength of individual posts. These vertical beams are the primary guard against intrusion into the passenger compartment.

Pioneer cab cars designed by Budd Company [32] were used in both tests. The cars were fitted with a new end structure: one a 1990's end frame, designed to pre-1999 industry standards, and the second with a State-of-the-Art (SOA) end frame, designed to meet current FRA regulations and APTA standards (updated in 1999).

The 1990's end frame consists of four vertical beams (two collision posts and two corner posts), two primary horizontal beams (the end beam and anti-telescoping plate) and includes a step well. The SOA end frame also consists of four vertical beams, two primary horizontal beams, but includes a continuous side sill and front facing sheets connecting the lateral member to the end beam. See Figure 10 for a design comparison.

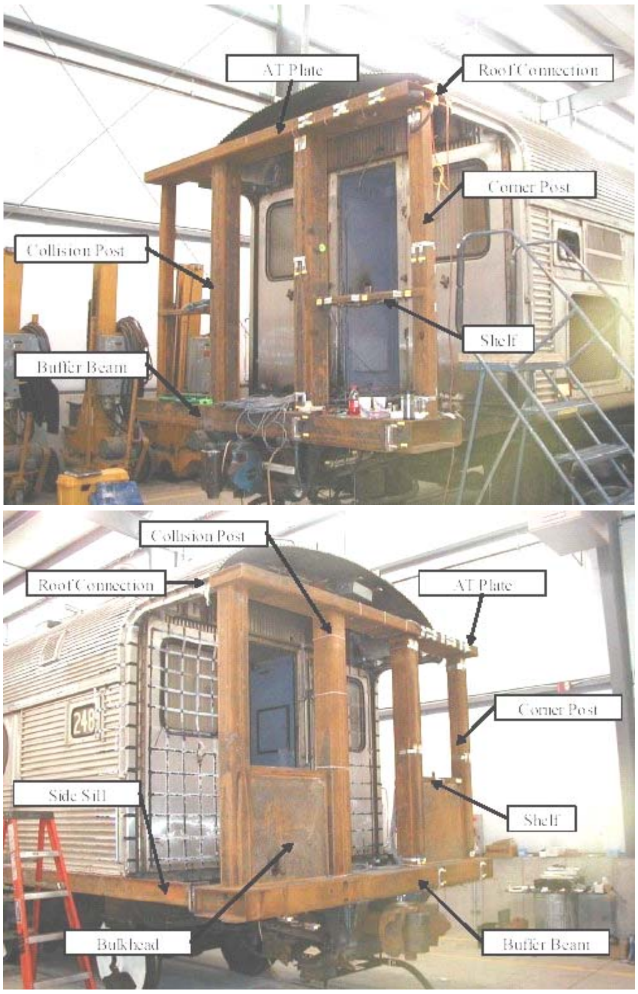

Figure 10. The modified cab car ends: 1990 design above, SOA design, below

Grade Crossing Tests Results

Figure 11 shows a photograph of the test setup for the 1990's design. The car was instrumented to measure the accelerations of the carbody, the displacements of the suspension, the displacements of the corner posts, and the strains in the selected structural members. In both tests, the cab car was pushed by a locomotive to a speed of 14 mph, then released and impacted the coil.

Figure 11. Setup of 1990's design test

Figure 12 shows the final deformed shapes taken from the tests of the 1990's design and the SOA design. During the test of the 1990's design, the corner post pulled out of its attachment at the top. The results of the test show that this corner post design is not sufficient to preserve the operator's volume in such an impact. During the SOA design test, the corner post remained attached. The maximum rearward deformation measured was approximately 8 ½ inches. The results of this test show that the SOA design is sufficient to prevent the operator from being crushed in such an impact.

Figure 12. Post-test photographs, 1990's and SOA end frames

5 Summary

Tests have been developed to measure the crashworthiness performance of rail passenger equipment in in-line train-to-train and grade-crossing impacts. For grade-crossing impacts, a test was developed for evaluating the crashworthiness of the corner structure of cab cars. This test has been applied to conventional and improved crashworthiness equipment. The results of these two tests show that the SOA design cab car is substantially more crashworthy that the 1990's design cab car. For in-line impacts, a sequence of three tests has been developed to measure the crush behavior of an individual car, the interaction of coupled cars, and the interaction of colliding equipment. These three tests have been applied to conventional U.S. rail passenger equipment. The results show that all the structural damage is focused on the impacting equipment, and that coupled equipment tends to buckle out laterally during impacts.

Preparations are underway for testing crash energy management design equipment in the three in-line tests. A corresponding series of single car, two car, and train-to-train tests are planned for crash energy management (CEM) equipment as were performed for the conventional 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, rather than focused on the leading end of the leading car. As a result there should be no intrusion into the occupant volume for the passengers. In addition, it is expected that all the cars will remain in-line during the train-to-train test of CEM equipment.

The results of this research are to be applied to the development Federal safety regulations. The FRA organized the Railway Safety Advisory Committee (RSAC) in

1996 with the purpose of developing recommended solutions to safety issues for the rail industry. The RSAC is a government/industry committee that includes all segments of the rail community – the railroads, the suppliers, and the unions. The RSAC has recently formed the Passenger Safety Working Group, and among the topics to be addressed by this group are passenger equipment structural crashworthiness and occupant protection. This Working Group was briefed on the results of the full-scale tests and the results of other ongoing research in rail equipment crashworthiness at its first meeting on September 9, 2003.

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