A Train-to-Train Impact Test of Crash Energy Management Passenger Rail Equipment

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CONTENT

Summary

This paper gives an overview of the in-line full-scale impact tests conducted by the Federal Railroad Administration and discusses a strategy for preventing override between colliding equipment. Override of the impacting equipment during a passenger train collision is often associated with substantial loss-of-occupant volume and consequent fatality. The full-scale impact tests have been used to explore the causes of override and confirm the effectiveness of the strategy for preventing override.

1 INTRODUCTION

The goal of the Federal Railroad Administration's (FRA) rail equipment crashworthiness research is to develop and evaluate practical concepts for increasing survivability in passenger train accidents. Alternative strategies for increased safety are first evaluated for potential effectiveness. For strategies that appear promising, designs are developed. Test articles are built and then tested. The tests confirm the design performance.

Members of the rail industry have had input to the test conditions and close access to the test results through various working groups. This research approach has been applied to structural crashworthiness and interior occupant protection strategies. Central to the research results is the information needed to develop specifications, standards, and regulations.

The results of FRA's research include the technology for designing, building, analyzing, and testing equipment with Crash Energy Management (CEM) features. Full-scale testing has been used to demonstrate the effectiveness of this technology. This paper includes an overview of the in-line full-scale impact tests conducted by FRA and a comparison of the crashworthiness of conventional and CEM equipment.

2 ARRANGEMENT OF TESTS

A series of tests have been conducted to compare the crashworthiness performance of existing equipment with the performance of equipment incorporating crushable end structures. The collision scenario addressed by these tests is a locomotive-led passenger train colliding with a cab car-led passenger train on tangent track. The tests carried out for each equipment type are:

1. Single-car impact into a fixed barrier
2. Two-car impact into a fixed barrier
3. Cab car-led train collision with standing locomotive-led train

The sequence of tests, shown schematically in Figure 1, allows the study of in-line collisions in increasing degrees of complexity. The conventional tests established crashworthiness performance of the existing fleet. The tests with equipment incorporating crushable end structures showed significant improvement over the current equipment.

Figure 1: Schematic Drawings of In-Line Impact Tests

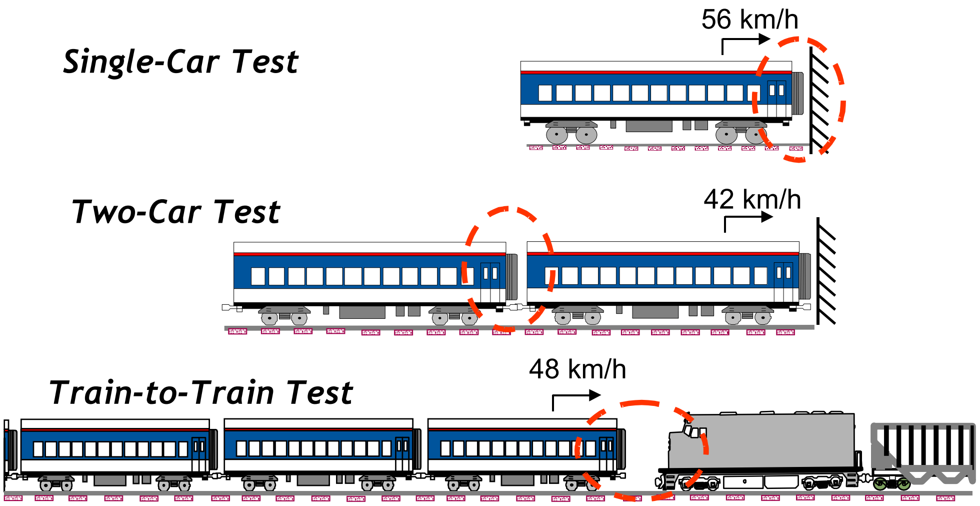


Table 1 lists the key measurements made during each test. In the single-car test, the critical measurements were made to obtain a force-crush characteristic and to measure the gross motions of the test equipment. The two-car test added consideration of the interactions of the coupled connection (i.e., measuring the vertical and lateral motions of the car respective to each other and observing the potential for sawtooth lateral buckling to occur). The train-to-train test focused on the interactions of the colliding equipment (i.e. how the equipment engaged and the potential for override of the colliding vehicles). Additionally, the effects of the collision throughout the train were measured.

Table 1. Arrangement of Tests and Principal Results

Test Description	**Critical Measurements**	**Results**	
		Conventional Equipment	**CEM Equipment**
Single-Car Test	Occupant volume	*Loss*	*Preserved*
	Force-crush characteristic	*Decreasing*	*Increasing*
	Mode of deformation	*Ramp*	*Controlled*
Two-Car Test	Occupant volume	*Loss*	*Preserved*
	Interaction of coupled cars	*Sawtooth buckled*	*Remained in-line*
	Distribution of crush	*Focused on impact car*	*Distributed*
Train-to-Train Test	Occupant volume	*Loss*	*Preserved*
	Colliding equipment interaction	*Override*	*Engagement*
	Interaction of coupled cars	*Sawtooth buckled*	*Remained in-line*
	Distribution of crush	*Focused on impact car*	*Distributed*

A secondary objective of the tests was related to the modeling development process. Computer models were used to predict the collision outcome and to determine the pre-test conditions. The models are modified based on the test results for future use in predicting outcomes for similar collision scenarios. While computer simulation models are not necessary to describe the results of the full-scale tests, they are critical to their conduct. Results from such models were used to determine the impact speed based on the predicted equipment damage. Size and placement of instrumentation was selected based on model predictions of the equipment's behavior during the test. In turn, these models have been refined using the test measurements. The results of the first three tests were especially useful in refining the models. For the fourth and subsequent tests, the pre-test predictions have been within the test's repeatability.

3 EQUIPMENT TESTED

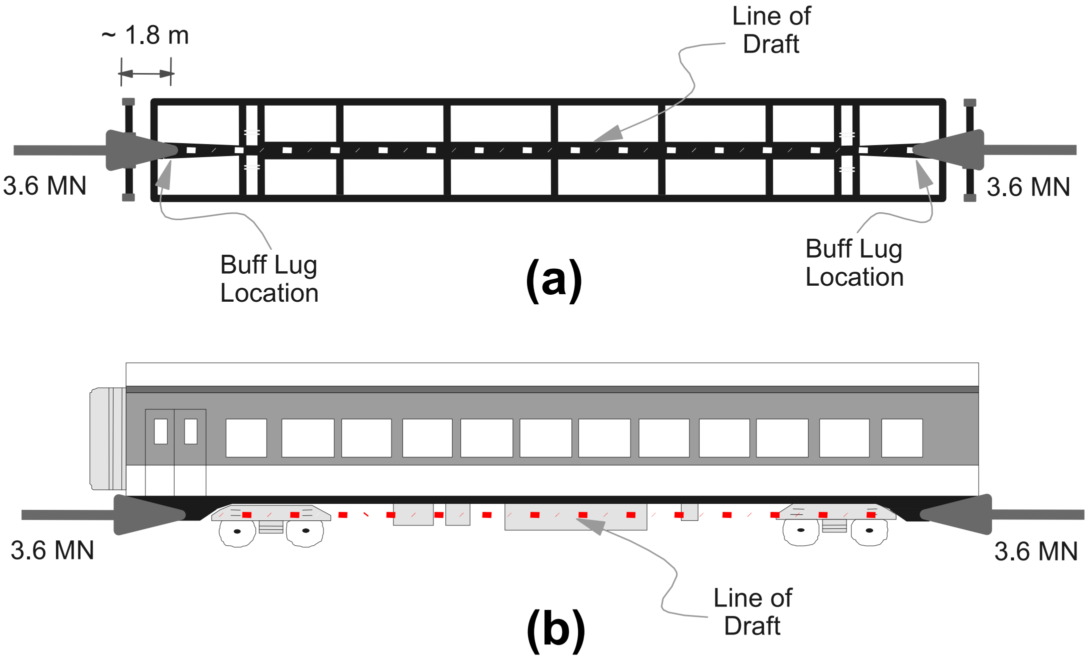
For conventional North American passenger rail equipment, the interactions of the impacting cars may be uncontrolled due to haphazard structural damage (crush), override, or buckling between cars. Structural damage tends to be focused on the colliding equipment and those cars immediately trailing. When passengers are in a leading cab car, structural damage can intrude into the occupant volume, resulting in a loss of survival space. Override is often associated with substantial loss-of-occupant volume and consequent fatality. The coupling between cars can lead to lateral buckling of the trainset

as a consequence of a collision. When viewed from above, the cars in the train form an accordion pattern. This lateral buckling of the train can lead to side-to-side impacts of the cars. Since the cars are relatively weak from the side, such impacts can also lead to loss-of-occupant volume and fatality.
To improve survivability, crush should be distributed to the unoccupied areas of the train, coupled car interactions should be restrained to limit lateral buckling, and the colliding interface should be controlled to prevent override. All of these goals can be achieved with crush zones, which are designed to gracefully deform when overloaded.

3.1 Conventional Equipment

Figure 2 is a schematic illustration of the principal structural members of a conventional car subjected to the principal North American crashworthiness requirement since the 1940s, an 3.6 MN buff load [1]. This requirement assures a minimum strength of the car's occupied volume. The buff stops are located approximately 1.8 m from the end of the car and support the compressive longitudinal loads from the coupler. Meeting this requirement using conventional design practices has resulted in structures that are nearly uniform in their axial strength.

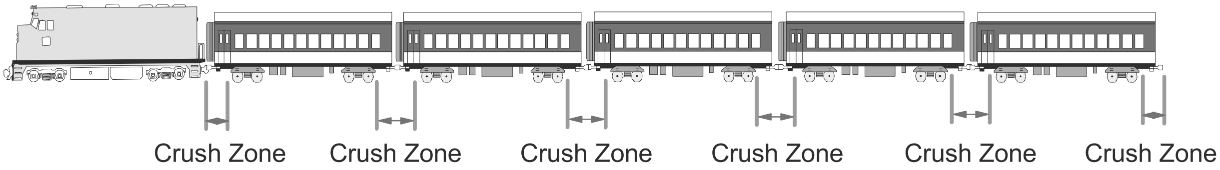
Figure 2: Schematic Illustration of Conventional Passenger Rail Car: (a) Top View, (b) Elevation View



3.2 CEM Equipment

Passenger rail equipment crashworthiness can be significantly increased if the force-crush behavior is engineered to take place in a controlled manner. Sacrificial crush zones can be designed into unoccupied locations in cars, such as brake and electrical service closets and bicycle storage areas, as well lightly occupied areas, such as vestibules and stairwells. These crush zones are designed to crush gracefully, with a lower initial force and increased average force. With such crush zones, multiple cars share energy absorption during the collision, consequently preserving the integrity of the occupied areas by managing the collision energy. The approach of including crush zones is termed CEM. Figure 3 is a schematic of the concept of CEM, with crush zones at the ends of all of the train's cars.

Figure 3. Schematic Illustration of Crush Zone Locations in Commuter Rail Passenger Train Used in Push-Pull Service



CEM extends from conventional crashworthiness design practice. The 3.6 MN buff strength requirement prescribes the strength of the structure that supports the crush zone. Greater buff strength allows greater crushing forces to be supported; in turn, greater energy can be absorbed for a given crush distance.

4 TEST RESULTS

This section presents an overview and describes the principal result of each of the six in-line tests. The section first discusses results of the train-to-train tests, to show the overall results of these six tests as quickly as possible. The results of the two-car tests are then discussed and finally the single car tests. Train collisions are complex events. The single-car tests are similar to the qualification tests done for automobiles. Such automotive qualification tests are well known and well understood. The two-car tests of rail equipment are somewhat more complex, and train-to-train tests are substantially more complex. The intent is to show the need to start from simple tests in order to successfully execute complex tests.

4.1 Train-to-Train Tests

Figure 4 includes frames from high-speed movies recorded at the train-to-train test of existing equipment and the train-to-train test of CEM equipment. In the train-to-train test of existing equipment [2], at a closing speed of 48 km/h, the colliding cab car crushed by approximately 6.7 m. Due to the crippling of the cab car structure, the cab car overrode the conventional locomotive. The space for the cab car operator's seat and for approximately 47 passenger seats was lost. During the train-to-train test of CEM equipment [3], at a closing speed of 50 km/h, the front of the cab car crushed by approximately 0.9 m. The controlled deformation of the cab car prevented override. All of the crew and passenger space was preserved.

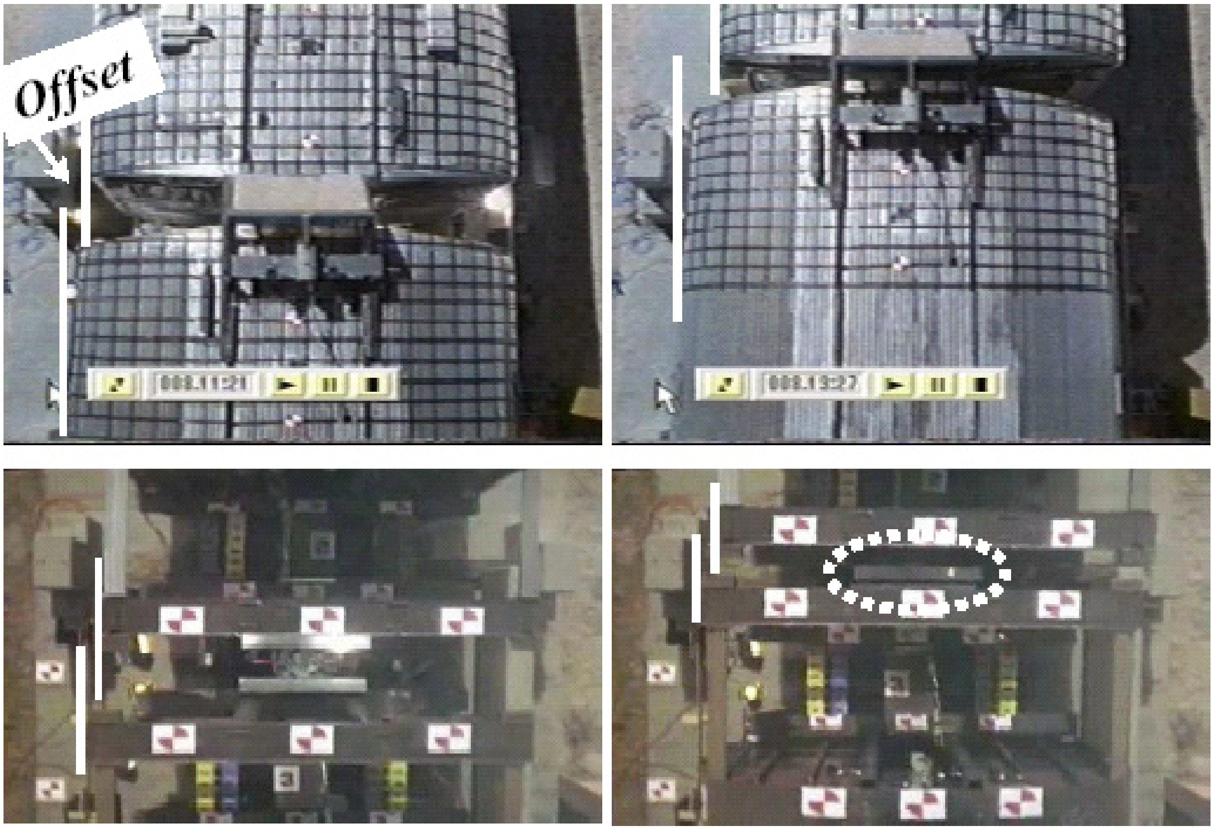
Figure 4: Frames from High-speed Movies of Conventional (top) and CEM (bottom) Train-to-Train Tests

4.2 Two-Car Tests

The two-car test of conventional equipment [4] was conducted at a closing speed of 42 km/h. The impact car crushed by approximately 1.8 m. No crush of the trailing car occurred. The crippling of the carbody structure caused the car to lift about 0.2 m. The conventional couplers caused the cars to buckle laterally. As a result of this misalignment of the coupled cars, the trucks immediately adjacent to the coupled connection derailed. The two-car test of CEM equipment [5] was conducted at a closing speed of 47 km/h. The cars preserved the occupant areas. The impact car crushed at the front and rear, and the trailing car crushed at the front. The pushback couplers allowed the cars to remain in-line with all of the wheels on the rails.

Figure 5 shows an overhead view of the stills from the high-speed camera for the conventional and CEM tests. The first photograph shows the cars at the time of impact (indicated by the flash of light). Relative lateral offset of the cars is marked with white lines in the photographs. In both tests, the cars were initially offset laterally by approximately 40 mm. The second still shows the offset at the time of maximum crush for each test. Sawtooth lateral buckling occurred in the conventional test, causing the rail to roll. As can be seen in the top photograph of Figure 5, the cars rested approximately 0.3 m out-of-line at the end of the collision. Contrastingly, in the CEM test, the cars remained in-line as the coupler pushed back and the anticlimbers engaged (indicated by the dotted oval). The test shows that the controlled collapse of the crush zones effectively helps keep the cars in-line.

Figure 5: Photographs of Coupled Interface for Conventional (top) and CEM (bottom) at Time of Impact (left) and Maximum Crush (right)

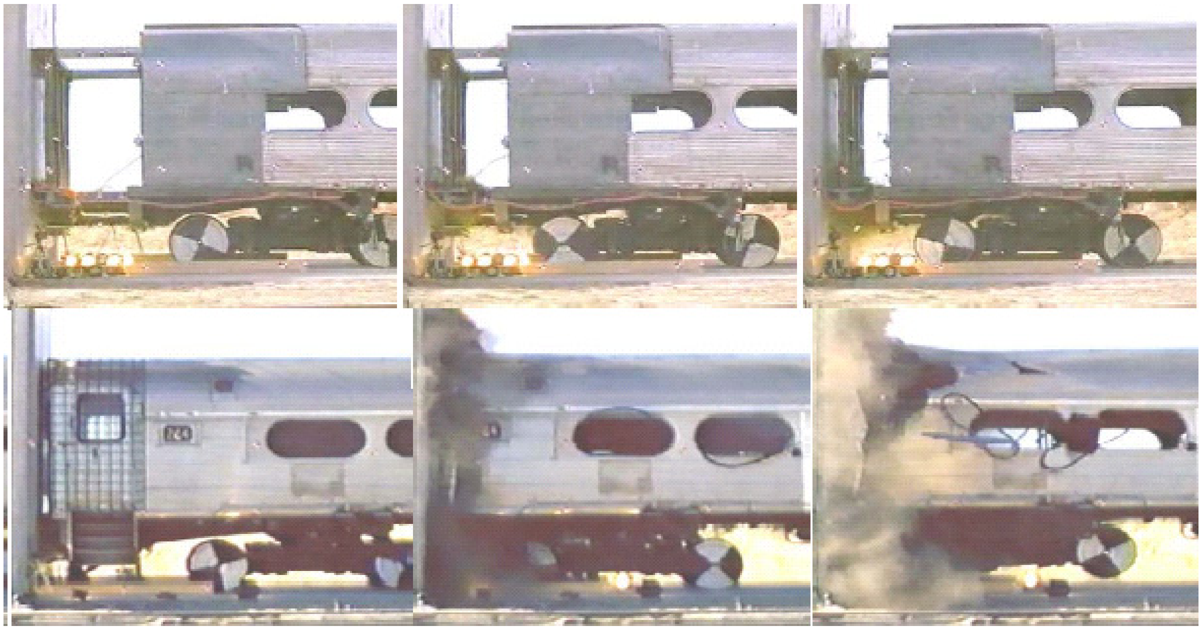


4.3 Single-Car Tests

The single-car test of conventional equipment [6] was conducted at a closing speed of 56 km/h. The car crushed by approximately 1.8 m, intruding into the occupied area. As a result of the crippling of the carbody structure, the car lifted by about 0.2 m, raising the wheels of the lead truck off the rails. The single-car test of CEM equipment [7] was conducted at a closing speed of 55 km/h. The CEM car crushed about 0.9 m, preserving the occupied area. As a result of the controlled crush of the carbody structure, its wheels remained on the rails.

The photographs in Figure 6 show three stills taken from the high-speed cameras of the CEM and conventional tests. These shots depict the time at which (1) the end frame contacts the wall, (2) midway through the collision, and (3) maximum crush of the test vehicles. As seen in the bottom half of Figure 6, the vertical motion of the carbody caused the front truck to lift off the tracks. These lateral and vertical motions are a result of the uncontrolled modes of deformation experienced by the draft sill. By employing longitudinally crushable elements in the CEM design, the crush is engineered to remain in-line, which in turn reduces the vertical motion.

Figure 6: Still Photographs of CEM (top) and Conventional (bottom) Full-Scale Tests



5 OVERRIDE: CAUSE AND PREVENTION

5.1 Conventional Equipment

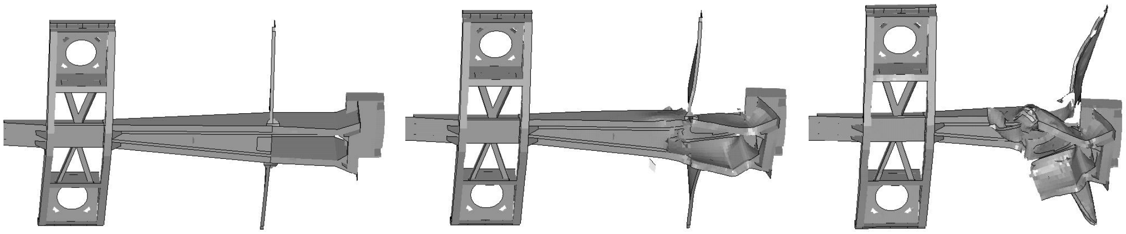
Override of conventional passenger rail equipment can occur due to the formation of a catapult-like mechanism behind the colliding interface. Figure 2 showed the principal underframe structural members for a conventional single level car. Conventional North American passenger car designs have a platform-like structure. The underframe is very stiff axially while the superstructure is much less stiff. When loaded in compression, such cars experience combined axial and bending deformations, which can lead to formation of a catapult-like mechanism.

For the single-car impact test, the end frame of the cab car remained intact and maintained contact with the rigid test wall, as shown in Figure 6. Initially, the load is transferred through the coupler. The draft gear bottoms out in the early stages of the test.

After the draft gear bottoms out, the main load-resisting element of the underframe—the draft sill/center sill—is overloaded and uncontrolled deformations ensue. These deformations started near the buff lugs that react the draft gear loads. Figure 7 shows the progression of the draft sill's deformation, taken from the post-test analysis of the single-car test [8]. The uncontrolled deformations behind the end frame resulted in the car moving up roughly 0.2 m. This is the initiation phase of override. This is an example of catapult mechanism formation due to deformations some distance behind the colliding interface.

The impact of the car into a rigid barrier is a scenario often used to describe two identical structures coming together at twice the impact speed. Even in the event of two like cars impacting one another, there is the possibility of override occurring as one car will likely be slightly stronger than the other car and crush will be focused on the overridden car. An example of this kind of behavior occurred in the Washington, DC subway incident where one car overrode a similar standing car [9].

Figure 7: Deformation Sequence of Draft Sill from Analysis of Conventional Single Car Impact Test–Uncontrolled Crush

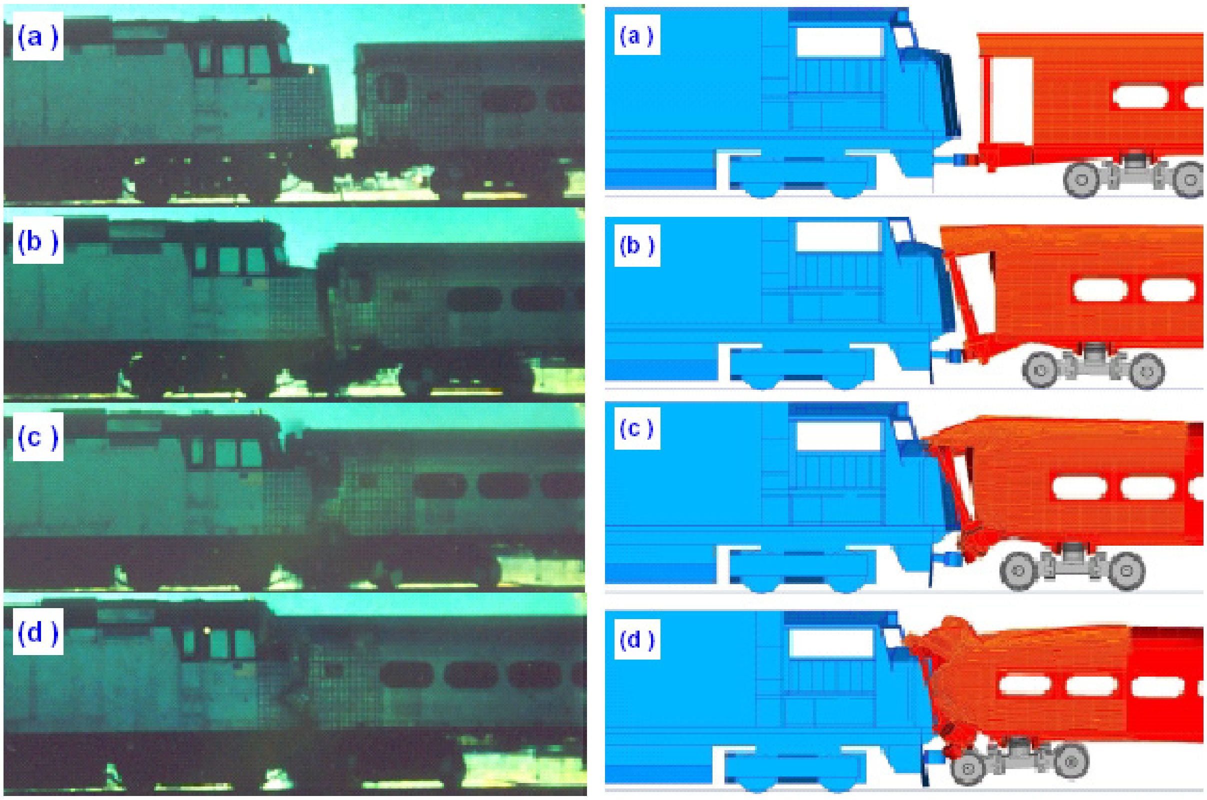


An impact of two dissimilar pieces of equipment was the collision condition chosen for the train-to-train test. The override observed at the conventional train-to-train test was also due to the formation of a catapult mechanism. Figure 8 shows a comparision of the detailed post-test modeling of the conventional train-to-train test with still photographs extracted from the high-speed film footage.

Understanding the sequence of events leading to override is crtitical to developing strategies for preventing override. Four states in the deformation sequence exist: initial contact, overload of the draft gear and failure of the connections of the end frame with the roof structure, catapult mechanism formation, and override initiaion. The locomotive draft gear housing is stronger than that of the cab car. So when both sets of draft gear bottom out, the uncontrolled deformations occur in the weaker of the two draft gear housings. This large longitudinal load is applied below the center of gravity of the cab car and results in axial and bending deformations. The connections of the end frame to the roof/cant rails fail, and the end frame rotates and sticks to the locomotive front hood structure. The locomotive anti-climber effectively holds the cab car end frame in place, which is evident in the remaining photographs in the deformation sequence. The deformation of structure behind the end frame promotes catapult mechanism formation, and the cab car overrides the locomotive. The trucks have risen above the rail in the last photograph and model deformation state, indicating that override initiation has commenced.

The lessons learned from the conventional train-to-train test are that it is important to deal with the interactions at the colliding interface and control how the load enters the carbody structure such that undesired/uncontrolled deformations do not occur. It is difficult to manage the significant concentrated loads that arise in a collision in a single strucutrual member, like the draft sill. Instead, load should be distributed over as large an area as possible.

Figure 8: Override Initiation for Conventional Equipment Train-to-Train Test, Observations and Analysis Results



5.2 CEM Equipment

Application of a CEM design strategy is effective in assuring that the energy that arises from a collision is managed in a controlled manner over many interfaces. Management of the impact interface—override prevention—is addressed with the CEM cab car design tested in the March 23, 2006, train-to-train test. Figure 9 is a schematic of the cab car crush zone design features. The cab car crush zone concept includes the following four key elements:

1. A pushback coupler mechanism
2. A deformable anti-climber arrangement
3. An integrated end frame, which incorporates an operator volume
4. Roof and primary energy absorbing elements

Figure 9: Schematic of Cab Car Crush Zone Conceptual Design (Side View)

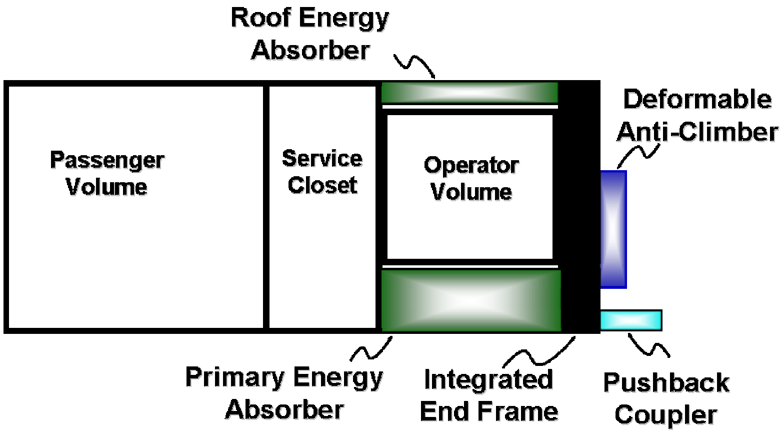
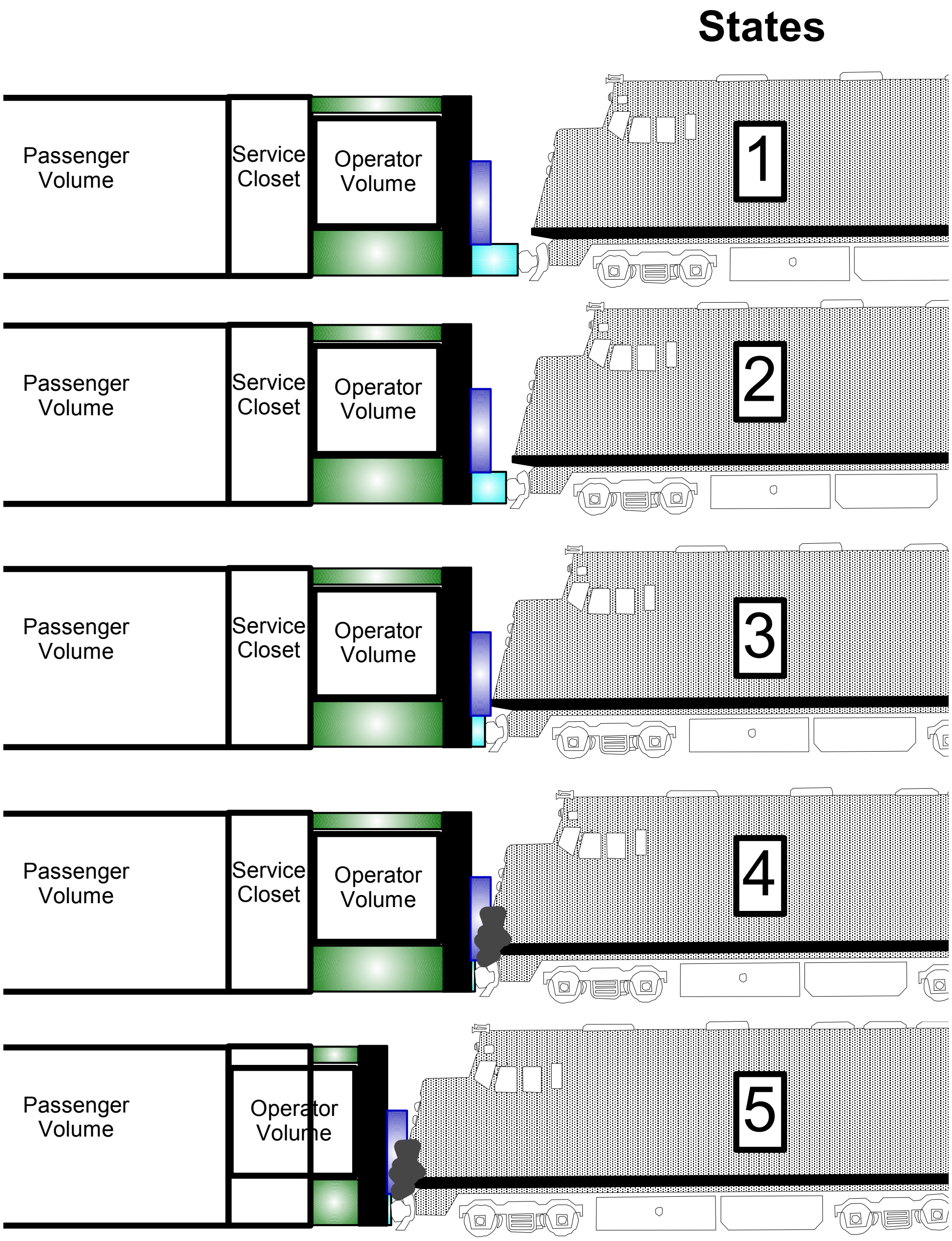


Figure 10 is a schematic illustrating the idealized kinematics of the cab car crush zone design. The couplers of the colliding equipment contact one another, as shown in state 1. After the stroke of both sets of draft gears are exhausted, the load increases on the structural fuse and activates when a prescribed load range is met, as shown in state 2. After some crush occurs in the pushback coupler energy absorber, the deformable anticlimber is also engaged, as shown in state 3. During this state, the load is shared between the anti-climber and the coupler. Next, when the combined load on the coupler and the deformable anti-climber reaches the prescribed trigger load range, the energy absorber structural fuse releases in state 4. The primary and roof absorbers crush and reach state 5 when their stroke is exhausted.

Figure 10: Schematic of Idealized Kinematic Cab Car Response



Override is effectively prevented by this type of design because the load path into the carbody structure is carefully controlled. Rather than allowing load to concentrate over a single structural member, load is instead shed as widely as possible across the full front face of the cab car end frame. The deformable anti-climber has been designed to conform to the uneven shape of the locomotive front end and resolve non-longitudinal loads into longitudinal loads that are then distributed through the integrated end frame. The integrated end frame must be sufficiently stiff so that only very small deformtions occur in it. This is required so that the load transferred through integrated end frame enters the energy absorbers in a manner for which the energy absorbers have been designed to resist—longitudinally. The placement of the energy absorbers is also important. By placing energy absorbers at the floor level and in the side walls or roof, added support helps to resolve all the loads entering the intergated end frame so that rotation of the end frame is resisted by counter-balancing moments.

6 DISCUSSION

FRA's research has shown that CEM can be effectively applied to North American passenger rail equipment. Effectiveness studies showed the promise of CEM [10]; crush zone designs were then developed [11]; example crush zones were retrofit onto existing cars; finally tests were conducted that demonstrated the effectiveness of CEM [3, 5, and 7]. In the train-to-train test of conventional equipment, the space for approximately 47 passengers and the operator was destroyed. Under the same impact conditions, the CEM equipment preserved the space for all of the occupants.

CEM works by assuring that the equipment structures gracefully deform when overloaded. Graceful deformation of the equipment structures allows override to be prevented, keeps the trailing equipment from buckling laterally, and distributes structural damage to the unoccupied areas of the train. Management of the impact interface is essential to preventing override. Such management can be effectively accomplished with a pushback coupler mechanism, a deformable anti-climber arrangement, an integrated end frame, and energy absorbing elements. Pushback coupler mechanisms are effective in preventing lateral buckling of coupled equipment. Integrated end frames and energy absorbing elements are essential to distributing crush to the unoccupied areas.

Metrolink, a commuter rail authority in Los Angeles, was preparing to purchase new equipment at the time of a fatal collision in Glendale, California. Eleven lives were lost in this incident, in which a cab car-led train ran into a locomotive-led train. As part of its response to the incident, Metrolink decided to incorporate recent results of FRA's passenger train crashworthiness research to its ongoing procurement. In coordination with the American Public Transportation Association (APTA), Metrolink approached FRA and the Federal Transit Administration (FTA). FRA, FTA, and APTA decided to form the ad hoc CEM Working Group in May 2005. This working group included government engineers and participants from the rail industry, including passenger railroads, suppliers, labor organizations, and industry consultants. The Volpe Center provided technical information on CEM to the working group. The working group developed a detailed technical specification in just over four months [12].

Metrolink released its specification as part of an invitation for bid in September 2005. In May 2006, the award was made to Rotem, a division of Hyundai, which manufactures rail equipment. FRA and the Volpe Center are continuing to work with Metrolink to assure that the supplier meets the requirements. New equipment with the CEM features is expected to be in service in 2009.

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