

Improved Crashworthiness of Rail Passenger Equipment in the United States

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Abstract

The Federal Railroad Administration has been conducting research to develop strategies for improved passenger protection in train accidents. Crash energy management (CEM) has been developed as a strategy for structural crashworthiness. Interior strategies that have been developed to work in concert with CEM include improved workstation tables and optimized commuter seats. The purpose of this research is to develop the technical information required for passenger equipment specifications, standards, and regulations. Research results are being applied by METROLINK commuter railroad in their current efforts to procure new equipment. The American Public Transportation Association is planning to develop industry standards from these research results.

Alternative strategies for structural crashworthiness and occupant protection are first evaluated for potential effectiveness. For strategies that appear promising, designs are developed; test articles are built and then tested. The effectiveness studies define the crashworthiness design requirements; the design studies show what is feasible. The design studies result in drawings, which are used to build test articles. The construction of test articles requires that the designs be sound. The tests confirm the design performance; the test conditions are derived from the effectiveness studies; and the test results are used to refine the effectiveness studies. This research methodology results in the information required to develop specifications, standards, and regulations.

For some collision conditions, CEM equipment can protect all of the occupants for closing speeds that are more than twice the speed for conventional equipment. Preserving the space for the occupants does marginally increase the deceleration of the CEM cab car. For trailing equipment, the decelerations are similar in CEM and conventional trains. The improved workstation table and optimized commuter passenger seat designs have been developed to mitigate the marginal increase in deceleration. The research on workstation tables has been carried out cooperatively with the United Kingdom's Rail Safety and Standards Board. Crashworthiness can be incrementally improved by the strategic addition of CEM and occupant protection features.

Full-scale impact tests have been arranged to allow direct comparison of the crashworthiness performance of conventional and alternative strategies. Single-car and two-car impact tests of conventional and CEM equipment have been conducted. These tests have shown that CEM can preserve the occupant volume and limit the likelihood of derailment. In these tests, the conventional equipment lost occupant volume and derailed. In the train-to-train tests, a cab car led train traveling at 30 mph impacts a standing locomotive led train. In the conventional equipment test, the space for 48 occupants was eliminated. The CEM equipment test is planned for March 23, 2006. It is expected that the space for all of the occupants will be preserved and that injury criteria values will remain within survivable limits. Instrumented test dummies in the cab and first coach cars will be used to confirm these expectations.

What's new?

Conventional and CEM equipment can safely be used in the same trains and CEM equipment can be introduced on a car-by-car basis, rather than a train-by-train basis.

1. Introduction

The Federal Railroad Administration (FRA), with assistance from the Volpe Center, has been conducting research on passenger rail equipment crashworthiness [1] to develop technical information needed by FRA to promulgate passenger rail equipment safety regulations [2]. The principal focus of passenger rail equipment crashworthiness research has been the development of structural crashworthiness and interior occupant protection strategies. Two collision scenarios have been addressed in passenger rail equipment crashworthiness research, a cab car to locomotive train-to-train collision [3] and a cab car to steel coil grade-crossing collision [4, 5]. Full-scale passenger rail equipment impact tests have been conducted to allow direct comparison of conventional and alternative crashworthiness strategies [5, 6]. Relatively simple models are initially developed to plan the tests. If these models do not provide sufficient detailed information, more complex models are used to address specific issues. The models are verified using the test results. They are then used to extrapolate from the test conditions.

Structural crashworthiness strategies developed by the research include:

- Cab end and non-cab end crush zones that essentially double the survivable speed (i.e., the maximum collision speed for which all of the occupants are expected to survive) for cab car-to-locomotive train-to-train collisions [7, 8, 9]
- Optimized cab car end frames that increase the survivable speed by 50 percent in grade-crossing collisions [10]

Occupant protection strategies developed include:

- Improved workstation tables which limit abdominal loads to survivable levels [11, 12]
- Optimized commuter seats which minimize head decelerations, neck loads, and chest decelerations, both forward-facing and rearward-facing [13]
- Seats incorporating lap and shoulder belts to restrain intercity and commuter passengers [14]
- Inflatable structures to compartmentalize the operator [15]

2. Accident Observations

The behavior of a train during a collision is influenced by the interactions of the colliding cars, the nature of the coupling between the cars, and the crush behavior of the individual cars. The interactions of the impacting cars can result in one car overriding the other car. Override is often associated with substantial loss of occupant volume and consequent fatality.

For conventional North American rail passenger equipment, 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. The structural damage tends to be focused on the colliding cars and those cars immediately trailing the colliding cars. Cars away from the colliding cars often remain structurally intact.

Even in a train collision that is nominally head-on -that is the impacting cars are initially in-line and their centerlines coincident-one impacting car may override the other or the impacting cars may laterally deflect past each other. The tendency to override or laterally deflect depends upon how the structures of the cars crush and the dynamic responses of the cars in the train to the impact force, as well as the initial conditions of the impact. The mode of crushing of some car structures may effectively form a ramp, leading to vertical or lateral forces that are sufficient to cause override or lateral deflection. The dynamic motions of the car can potentially contribute to misalignment of the underframes, amplifying the tendency toward override or lateral deflection.

Figure 1 shows a photograph of an incident which occurred on January 26, 2005 in Glendale, California, in which a cab car led commuter train derailed due to an impact with an SUV on the track, and subsequently collided with a freight train parked in a siding. During the collision with the freight train, the cab car led train raked a locomotive led commuter train on the adjacent mainline track.



Figure 1. Aerial Photograph of Glendale Incident

The results of train incidents such as Glendale show that to preserve the occupant volume, it is important to restrain coupled car interactions to limit lateral buckling and to control the colliding interface to prevent override. These goals can be achieved by designing structures that gracefully deform when overloaded. By managing the energy absorption during a collision, the occupant volumes can be better preserved while the decelerations of the occupant volumes can be limited.

3. Structural Crashworthiness

Cab car led trains present a challenging situation in collisions. The presence of passengers in cars of lighter weight and lower strength in comparison with locomotives presents a potential hazard in the event of a collision. To address this exposure, FRA has conducted research on strategies intended to improve the crashworthiness of cab cars [16, 17, 18, 19, 20]. One alternative strategy is not to permit cab car led trains and require a locomotive in the lead. Another alternative strategy is to use equipment with crash energy management (CEM) [18, 21]. CEM improves crashworthiness with crush zones at the ends of the cars. These zones are designed to collapse in a controlled fashion during a collision, distributing the crush among the unoccupied ends of the cars of the train. This technique preserves the occupied spaces in the train and limits the decelerations of the occupant volumes. A third alternative strategy is to combine a locomotive in the lead with CEM.

The crashworthiness provided by the three alternative strategies has been compared with that of the baseline conventional cab car led train [22]. A collision with a locomotive led train has been used for the comparison. Loss of occupant volume and secondary impact velocity (SIV) has been used to estimate fatalities as a function of closing speed for the baseline and three alternative strategies. The higher the SIV, the more likely the occupants will be injured due to striking an interior surface. The research has shown that a CEM cab car led train has greater crashworthiness than a conventional locomotive led train and that a locomotive led CEM train provides the highest level of crashworthiness.

These research results show that passenger train crashworthiness can be incrementally increased by first incorporating CEM in the cab car, then by modifying the coach cars with pushback couplers, and finally by incorporating CEM in the coach cars.

Evaluation of the crashworthiness of trains made up of mixed CEM and conventional equipment has shown that a mixed CEM-conventional train is always at least as crashworthy as an all-conventional train and is more crashworthy when the CEM equipment is nearest the impact [23]. The modeling results indicate that the least crashworthy consists are ones in which a conventional cab car is leading any combination of vehicles. The conventional cab car incurs nearly all the damage and prevents trailing cars from participating in energy absorption, whether they are conventional or CEM. The most crashworthy consists are ones in which a CEM cab is leading. The CEM cab can absorb a significant amount of energy without intruding into the occupied volume. The CEM cab also allows trailing cars to participate in energy absorption, which provides further occupant protection.

Figure 2 shows simulation results for the amount of occupant volume lost in the impact cab car for closing speeds up to 40 mph, for a cab car led train collision with a locomotive-led train of equal weight. The passenger equipment modeled is single level with end vestibules. This figure contains plots for an all-conventional train, a train with a CEM cab car with conventional coach cars, a train with a CEM cab car with conventional coaches modified with pushback coupler, and an all CEM train. By changing only the cab car from conventional to CEM, the crashworthy

speed (the maximum speed for which there is no occupant volume crush) increases from 15 mph to 25 mph. A substantial increase in crashworthiness can be achieved by including crush zones one car in the train. By further changing the coach cars to have pushback couplers, but otherwise conventional structures, the crashworthy speed can be further increased to 28 mph. A pushback coupler allows for a relatively modest amount of energy absorption under collision conditions. This result suggests that a further increase in crashworthiness can be achieved by relatively minor modification to existing equipment. The fourth plot on the graph shows that an all CEM train has a crashworthy speed of 38 mph.

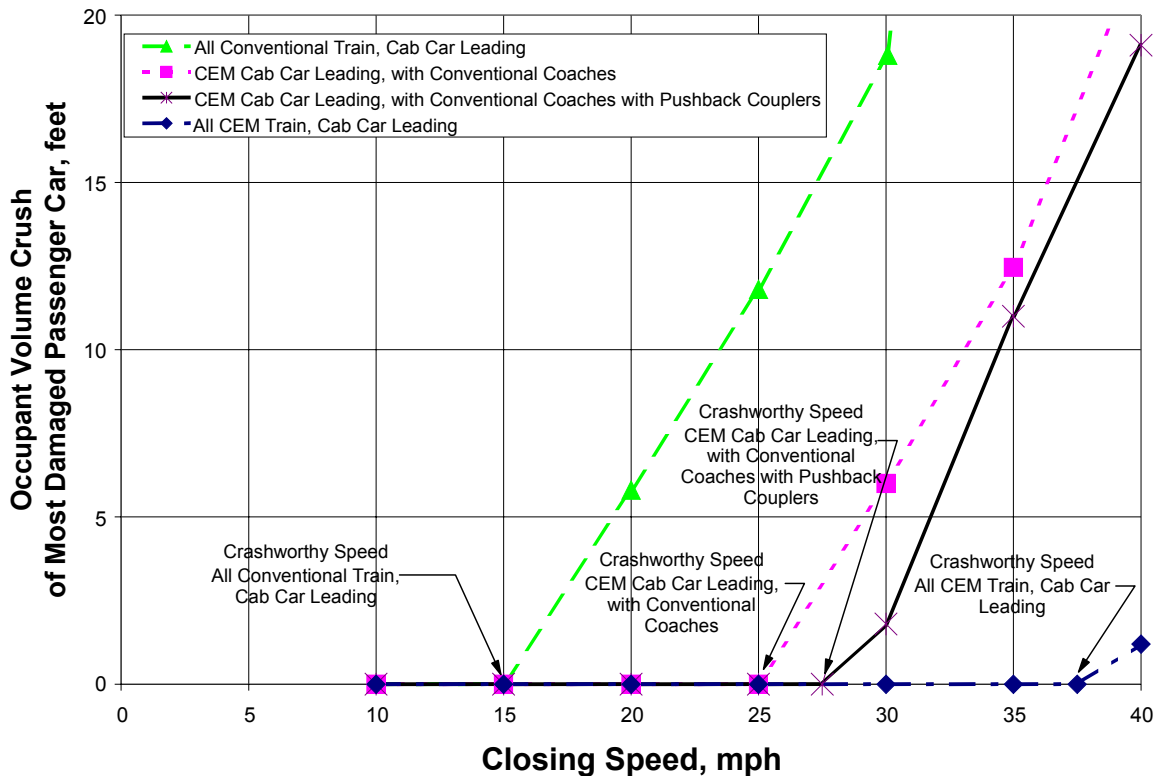


Figure 2. Occupant Volume Crush Results for Varying Closing Speeds

These research results suggest that a railroad can incrementally increase structural crashworthiness as it purchases and overhauls equipment. When new equipment is purchased, it should be to first replace existing cab cars with CEM cab cars. When existing equipment is overhauled, relatively minor modifications can be made to retrofit the equipment with pushback couplers. These changes will bring the crashworthiness speed of the trains up to the same level as adding a lead locomotive. After the conventional cab cars are replaced with CEM cab cars, the coach cars can be replaced with CEM coach cars. An all CEM train has a higher crashworthiness speed than a conventional locomotive led train.

4. Occupant Protection

In the FRA's crashworthiness research, SIV has been used to calculate injuries caused by an occupant impacting an interior part of the car. SIV refers to the velocity at which an occupant strikes some part of the interior, such as the forward seat back. To estimate occupant injury, test data have been used to correlate SIV with head, chest and neck injury for specific interior arrangements. Figure 3 shows a representative SIV plot for a cab car in a 35 mph train-to-train collision. The figure shows various seating configurations in relation to allowable travel distances. Typically, a shorter travel distance correlates to a lower SIV, as less time is allowed to build up relative velocity.

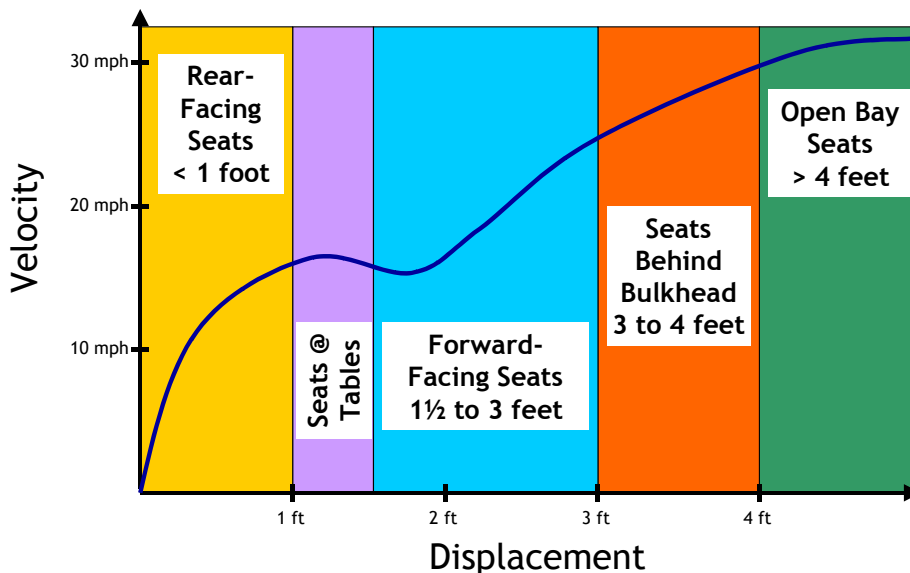


Figure 3. Representative SIV Plot Corresponding to Various Seating Configurations

The plot in Figure 4 shows the severity of SIVs and the possible measures for mitigating the likelihood for injury. A secondary collision environment of less than 18 mph SIV is survivable with conventional interior equipment. Between 18-25 mph SIVs, the interior environment is deemed survivable if compartmentalization is ensured and passive safety modifications are provided in the seat and table designs. Above 25 mph, active protection features (i.e. air bags, inflatable structures, seatbelts, etc.) are necessary to reduce the risk of injury.

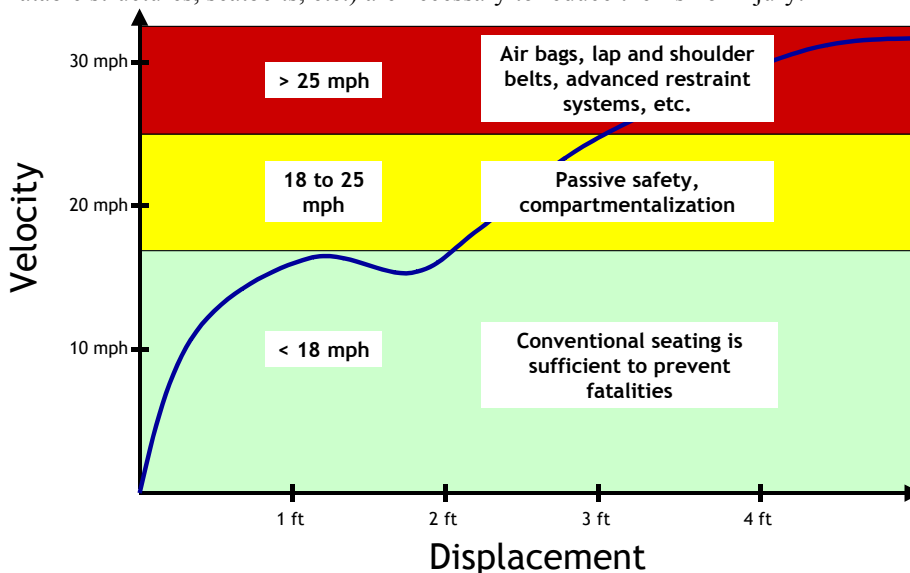


Figure 4. Example SIV Plot with Injury Interpretation

Trains with CEM cab cars leading are expected to have SIVs in the 18 to 25 mph range in the cab car for train-to-train collisions at primary collision speeds greater than 25 mph. Trains with conventional cab cars are expected to have SIVs of less than 18 mph in the cab car. (The SIV is typically lower than the primary collision speed because the occupant generally impacts the interior before the primary collision is finished.) Trailing equipment is expected to have SIVs below 18 mph, regardless of the leading equipment—CEM cab, conventional cab, or conventional locomotive. Occupant protection measures greater than those provided by conventional interior fixtures are required in CEM cab cars to mitigate the potential for occupant injury in train-to-train collisions with closing speeds above 25 mph.

The probability of injury in CEM cab cars can be mitigated by incorporating better interior designs, such as rear-facing seats with high enough head rests that protect against neck injury. Referring back to Figure 3, rear-facing seats allow for a travel distance of between zero and 1 foot and, consequently, results in a low SIV. Optimized commuter seats, which provide more energy absorption capacity than conventional seats [13], and improved workstation tables [12], which limit the load into the occupant's abdomen, have been developed to reduce injury due to secondary impacts for unrestrained passengers. These strategies can protect passengers in a CEM cab car at least as well as conventional fixtures in a conventional cab car.

5. Design and Build

Cab and non-cab end crush zones, optimized commuter seats, and improved workstation tables have been designed and built. A key product of the design development is a detailed description of the design requirements. These requirements describe the functions of the design. Construction of test articles shows that it is practical to build equipment and components with these functions.

5.1 Crush Zones

The principal goal for both the cab car and coach car crush zone design is to protect the passenger volume. To achieve this goal, the coach car crush zone is required to absorb 2.5 million ft-lbs of energy per car end and to deform gracefully when it crushes, minimizing vertical and lateral car motions [8]. The cab car crush zone is required to absorb 3.0 million ft-lbs per cab end. In addition, it must crush gracefully and manage the impact with colliding equipment, to prevent override [9].

Figure 5 shows a photograph of a cab end crush zone test article that was developed as part of the research. The key elements of the design include features to control the colliding interface interaction, a fixed/sliding sill interface that allows push back of the entire front end structure of the cab car into the service closet space, and a set of primary and roof energy absorbers. The elements that help manage the interactions of coupled cars are the pushback coupler and the coupled end load distributor. The coupled end load distributor acts to transmit the longitudinal collision load between cars. The pushback coupler is designed to translate longitudinally and allow the ends of the equipment to come together, without developing sufficient lateral load to derail the equipment. The elements that help manage the interaction with colliding equipment are the pushback coupler and the cab end load distributor. The cab end load distributor is deformable and acts to resolve off-axis loads from the impact into loads that can be supported by the integrated end frame, which in turn imparts suitable loads to the energy absorbers.



Figure 5. Crush Zone Final Design

5.2 Workstation Tables

Strategies to mitigate the potential for injury due to impacts with workstation tables are being developed through a cooperative agreement between FRA of the United States and the Rail Safety and Standards Board (RSSB) of the United Kingdom [11]. RSSB and FRA have shared the results of ongoing work to improve the safety of passengers seated at tables. RSSB has loaned the FRA its test dummy, the H3RS. This test dummy includes sensors to measure the loads imparted by workstation tables under collision conditions. This test dummy has been used to measure the performance of the baseline table and will be used to measure the performance of the improved table.

The improved workstation table was designed to meet crashworthiness performance, functionality, and geometry requirements [12]. Once the table is fabricated, it will be tested both quasi-statically and dynamically, including two occupant experiments on the full-scale train-to-train impact test of CEM equipment. Figure 6 shows a sketch of the design.

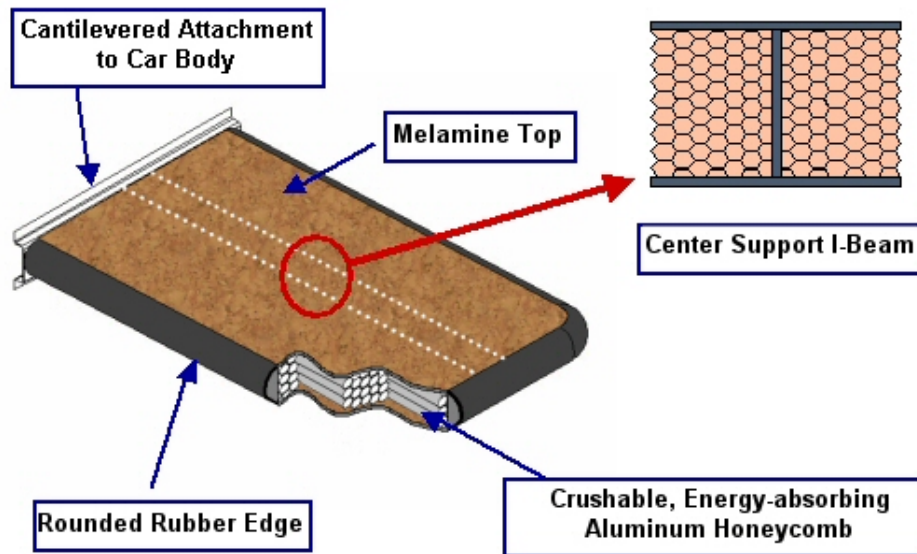


Figure 6. Preliminary Design of an Improved Workstation Table

This design builds from a center support I-beam, which is cantilevered from the car wall, and extends laterally from the wall to the aisle. The center support I-beam is designed to remain attached under the impact loads from two occupants during a collision, ensuring that the occupants remain compartmentalized. It also supports the table under service loads. The table edge is constructed of a crushable, energy-absorbing aluminum honeycomb, oriented so that cells are aligned in the vertical direction. This allows for the table edge to achieve the target force-crush characteristic while remaining stiff enough to meet the service load requirements. The melamine tabletop provides a rigid surface to preserve the functionality of the table. Connections between the tabletop and the aluminum honeycomb edge provide additional support in meeting the service load requirements. During impact, the melamine top is designed to break away in such a manner that it will not adversely affect the force-crush characteristic. The rubber edge distributes the load from the melamine top and the aluminum honeycomb to provide a benign impact surface to the occupants during a collision.

6. Full-Scale Tests

The crush zone and improved workstation table designs have been developed and built for full-scale testing. Crush zones have been tested in single-car and two-car impact tests. Crush zones will be further tested in the train-to-train test of CEM equipment on March 23, 2006. The improved workstation table will be tested concurrently during the train-to-train test of CEM equipment.

The results from the full-scale impact tests to date show that the CEM design has superior crashworthiness performance over conventional equipment. In the single car test of conventional equipment, the car crushed by approximately 6 feet, intruding into the occupied area, and lifted by about 9 inches, raising the wheels of the lead

truck off the rails [25]. Under the same single-car test conditions, the CEM trailer car crushed approximately 3 feet, preserving the occupied area, and its wheels remained on the rails [26].

In the two-car test of conventional equipment, the impacting conventional car again crushed by approximately 6 feet and lifted about 9 inches as it crushed; in addition, the coupled cars sawtooth-buckled, and the trucks immediately adjacent to the coupled connection derailed [27]. In the two-car test of CEM equipment, the cars preserved the occupant areas and remained in-line, with all of the wheels on the rails [28].

In the train-to-train test of conventional equipment, the colliding cab car crushed by approximately 22 feet and overrode the locomotive [29]. The space for the operator’s seat and for approximately 47 passenger seats was lost. Figure 7 shows a comparison between the conventional train-to-train test and the predictions of a crush model for the CEM train-to-train test. Computer simulations of the train-to-train test of CEM equipment indicate that the front of the cab car will crush by approximately 3 feet and that override will be prevented [30]. Structural crush will be pushed back to all of the trailer car crush zones, and all of the crew and passenger space will be preserved. The train-to-train test of CEM equipment, which is planned for March 23, 2006, is expected to confirm these predictions.

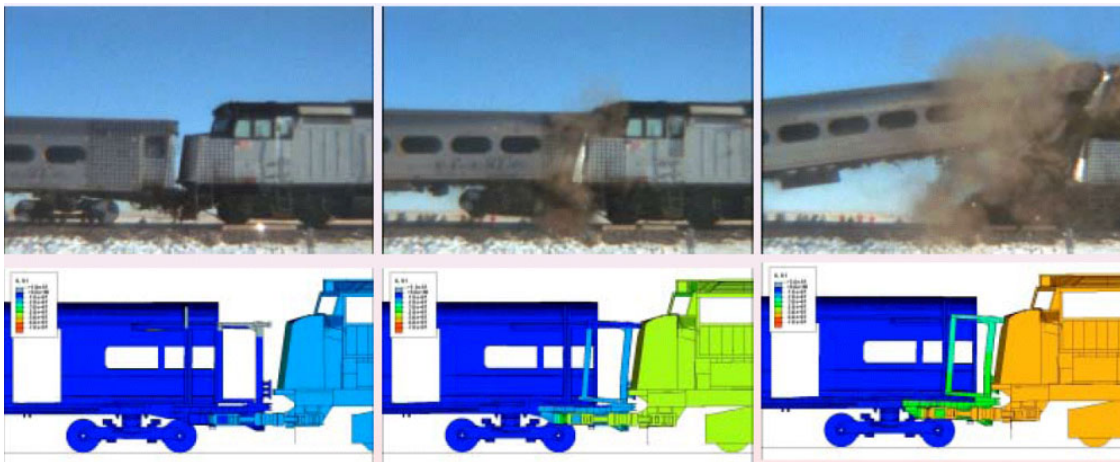


Figure 7. Conventional Train-to-Train Test Result and CEM Train-to-Train Test Prediction

On the CEM full-scale two-car impact test conducted on February 26, 2004, two experiments involved the facing-seats with intervening workstation tables [31]. These experiments used advanced test dummies to measure the abdominal response to the table impact. Figure 8 shows stills from the high-speed movies taken during this test, for both the RSSB’s Hybrid 3RS and the National Highway Transportation Safety Administration’s THOR advanced test dummies. This test confirmed the need for crashworthiness improvements in the design of the workstation table. Additionally, these test results serve as a point of reference to evaluate the performance of an improved design.

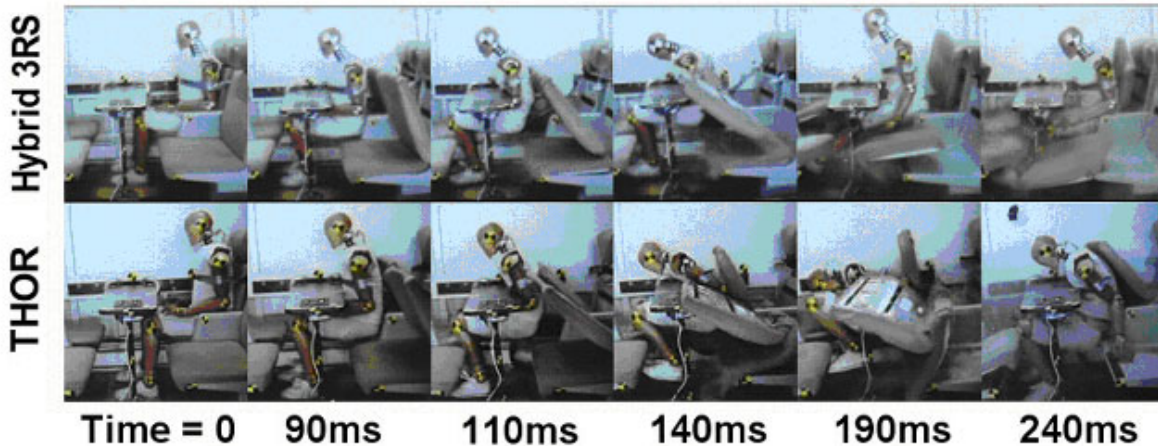


Figure 8. Hybrid 3RS Response during Two-Car Test

7. Summary and Application of Research Results

The modeling performed as part of the research shows the potential benefits of alternative crashworthiness strategies. The full-scale testing is used to confirm the effectiveness of the most promising strategies. Development of designs implementing these strategies results in detailed requirements. Fabrication of the test articles shows that such designs can be practically built. Information on costs to design and build is consequently developed while designing and building the test articles. This cost information is currently being used with information from the FRA field study and extrapolations from the full-scale testing to evaluate the economics of applying CEM.

At the time of the Glendale train incident on January 26, 2005, in which 11 commuter train occupants were fatally injured, METROLINK was preparing to purchase new equipment. As part of its response to the incident, METROLINK decided to apply recent results of the FRA's research into passenger train crashworthiness in this 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 participants from the rail industry, including passenger railroads, suppliers, unions, and industry consultants. Many of the participants in this Working Group also participate in the Railroad Safety Advisory Committee's [34] Crashworthiness/Glazing Task Force and in the APTA Construction/Structural Subcommittee. The CEM Working Group developed recommendations for crush zones in passenger rail cars for METROLINK to include in its procurement specification. METROLINK released its specification, including the recommendations from the Working Group, on September 16, 2005, as part of an invitation for bid.

The specification prescribes performance for the train, the cab and trailer cars, and the mechanisms [33]. Each requirement includes quantitative criteria for evaluation of compliance. The Working Group extensively discussed various evaluation methodologies, including non-linear large deformation finite element analysis and dynamic component tests, and worked to assure that practical evaluation methodologies are available for each requirement. For components critical to the functioning of the crush zone, tests are required.

These research results suggest that a railroad can incrementally increase crashworthiness as it purchases and overhauls equipment. When new equipment is purchased, it should be to first replace existing cab cars with CEM cab cars. When existing equipment is overhauled, relatively minor modifications can be made to retrofit the equipment with pushback couplers. These changes will bring the crashworthiness speed of the trains up to the same level as adding a lead locomotive. After the conventional cab cars are replaced with CEM cab cars, the coach cars can be replaced with CEM coach cars. Strategically incorporating CEM incrementally increases the crashworthiness speed and provides a practical solution for improvement in the rail industry.

The Standing Committee on Rail Transportation (SCORT) has expressed interest in adapting the METROLINK specification to its needs. During the final meeting of the ad hoc CEM Working Group, APTA stated its intention to use the METROLINK specification as a starting point for an industry standard, after METROLINK is close to accepting delivery of its new equipment, to be sure that any issues with the specification have been resolved. FRA is currently considering regulations for CEM.

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