Proceedings of ASME RTD 2004:
2004 ASME International Mechanical Engineering Congress
November 13-19, 2004, Anaheim, CA

IMECE2004-61601

Development of Crash Energy Management Designs for Existing Passenger Rail Vehicles

Eloy Martinez
David Tyrell
Volpe National Transportation Systems Center
US Department of Transportation
Cambridge, MA 02142 USA

Benjamin Perlman
Department of Mechanical Engineering
Tufts University
Medford, MA 02155

ABSTRACT

As part of the passenger equipment crashworthiness research, sponsored by the Federal Railroad Administration and supported by the Volpe Center, passenger coach and cab cars have been tested in in-line collision conditions. The purpose of these tests was to establish baseline levels of crashworthiness performance for the conventional equipment and demonstrate the minimum achievable levels of enhancement using performance based alternatives.

The alternative strategy pursued is the application of the crash energy management design philosophy. The goal is to provide a survivable volume where no intrusion occurs so that passengers can safely ride out the collision or derailment. In addition, lateral buckling and override modes of deformation are prevented from occurring. This behavior is contrasted with that observed from both full scale tests recently conducted and historical accidents where both lateral buckling and/or override occurs for conventionally designed equipment.

A prototype crash energy management coach car design has been developed and successfully tested in two full-scale tests. The design showed significant improvements over the conventional equipment similarly tested. The prototype design had to meet several key requirements including: it had to fit within the same operational volume of a conventional car, it had to be retrofitted onto a previously used car, and it had to be able to absorb a prescribed amount of energy within a maximum allowable crush distance. To achieve the last requirement, the shape of the force crush characteristic had to have tiered force plateaus over prescribed crush distances to allow for crush to be passed back from one crush zone to another. The distribution of crush along the consist length allows for significantly higher controlled energy absorption which results in higher safe closing speeds.

INTRODUCTION

North America has designed freight and passenger rail vehicles using strength based requirements. In the passenger rail industry, cars designed with stiff underframes and weaker superstructures are common. These designs were developed to withstand very large buff and draft forces during regular operations, the occasional hard shunts during consist management in yards, and collisions.

Current rail passenger equipment standards and regulations evolved from Railway Post Office (RPO) practice [1]. The RPO had a number of cars for carrying the mail; employees would sort the mail on these cars while the cars were traveling, often as part of a freight train. Early in the 20th Century, a number of accidents occurred in which the RPO cars were damaged and the employees were severely injured and/or killed. The damage to the RPO cars was a consequence of the large, long duration buff forces that can occur during accidents involving long freight trains. Initially, a requirement that the RPO car bodies withstand a buff load of 400,000 lbf without any permanent deformation was tried. This load was eventually increased to 800,000 lbf. Figure 1 shows an RPO car, circa 1940, of riveted steel construction.

Figure 1. Railway Post Office Car, Circa 1940.

The crashworthiness requirements for the RPO cars were developed to assure the preservation of survival space for occupants of a single car located somewhere in a long freight train. In the event of a collision or derailment the RPO car was subjected to long duration buff forces. These forces were taken as almost quasi-static in nature. Hence, the buff load requirement developed was very reasonable. In contrast, typical passenger car consist lengths today are considerably shorter than freight consists and the collision and/or derailment loads are dynamic in nature. Also, there is a need to preserve occupied volume in all the cars as opposed to a single car located somewhere in the consist. These differences in the nature of the forces and the requirements of the crush behavior of every car and the whole consist suggest that other requirements are needed in addition to the buff requirement.

Since the early 1990's there have been considerable advances in both analytical techniques and design practice. With the advent of such information a new design philosophy, known as crash energy management, is being pursued worldwide. The backbone of the approach is to dissipate the energy associated with a collision or derailment in a controlled manner. This is accomplished by allowing for designed progressive collapse in unoccupied areas of each car in the train. In contrast, for application of strength based design requirements, loads are specified for specific structural elements. The crash energy management approach addresses the behavior of the complete system to manage both energy absorption and vehicle trajectory along the length of the consist.

This approach is suitable for assuring the survival of occupants in accidents such as the 2002 passenger train-to-freight train collision in Placentia, California [2]. It assures preservation of survival space for the occupants in all of the cars. Studies conducted in the early 1990's in support of the Amtrak's high speed train procurement showed that the CEM approach had significant benefits in train-to-train collisions at closing speeds of 70 mph and greater [3]. As a result, Amtrak's specification required the incorporation of crush zones into the power car and transition car. A photograph of Amtrak's high-speed train is shown in Figure 2. Following modern practice, the carbody structure is of welded steel construction.

Figure 2. Intercity Passenger Train, Circa 2000

Full-scale testing has furnished measurement of the force required to crush a conventional car. The results of these tests are significantly different from the results of the analyses conducted in the 1970's [4]. This measured force/crush characteristic has been applied to simulations of a train-to-train collision in which a cab car impacts a locomotive [5, 6] and a cab car collides with a cab car [7]. The results of these simulations indicate that the benefits of CEM begin to accrue for train-to-train collisions in which the closing speeds are 13 mph or greater. Full-scale testing is being conducted in order to verify these results.

The full-scale testing program has measured the crashworthiness performance of conventional passenger equipment in a train-to-train collision, to establish a baseline for comparison with CEM equipment. As part of this effort, a crush zone design has been developed for integration into existing passenger cars [8]. This coach car design has already been tested in two full-scale tests. Work is ongoing on the preparation for a full-scale train-to-train test. A coach car design is being modified for retrofit to a cab car as part of the train-to-train test plan. Modifications include stronger collision and corner posts, the addition of anti-climbing features for impact conditions, and features to protect the operator.

This paper presents the approach taken to develop a passenger coach car crash energy management crush zone design. Design requirements were developed based upon results from the conventional testing and an accident history review. Several preliminary designs were developed. Full-scale subcomponent testing was conducted in conjunction with the development of the final design. The designs were then retrofitted onto existing passenger cars and tested in rigid barrier impact tests. The results from those tests are being used to compare the performance of the developed crush zone design with conventional equipment.

SUMMARY OF CONVENTIONAL EQUIPMENT FULL-SCALE IMPACT TESTS RELATED TO TRAIN-TO-TRAIN COLLISIONS

The results from the tests conducted to date have been well documented in the literature [9, 10, 11, 12, 13], so only the salient results from each in-line test will be discussed. Of particular interest are the development of the force crush characteristics for each test and the relation of the impacting, and coupled interfaces to subsequent trajectories of the cars. This information is useful to assist in the definition of requirements for the crash energy management crush zone.

The first test conducted was a conventional single car impact into a rigid barrier. The test was designed with sufficient energy that only a single row of passenger seats would be crushed. It is important to generate crush sufficient to characterize the vehicle but not so much that the result would become difficult to interpret. The key results from this test are the modes of deformation and the force crush characteristic.

The second test was a conventional two-car impact into a rigid barrier. Similar force crush characteristics were measured. In addition, the behavior at the colliding interface and at the coupled interface was of interest, adding to the complexity of the test. The crush was focused on the impact end of the lead car. There was essentially no structural damage at the coupled interface, but the cars buckled out laterally, derailing and rolling the rails.

The mode of deformation observed at the coupled interface is referred to as "Saw-tooth" or small scale lateral buckling. This type of deformation occurs due to the presence of the couplers pinned near the ends of both cars. The coupler acts like a rigid link between the cars and when a sufficiently large longitudinal load is applied through the couplers with small lateral perturbations present, the cars "kick out" to either side allowing the underframes to come together misaligned. If there is sufficient energy available from a collision, the small scale lateral buckling can evolve into the more dangerous form referred to as large scale lateral buckling. If this occurs, cars in a longer consist may foul the right-of-way of oncoming traffic and result in secondary collisions with other trains or obstructions with disastrous results for the passengers and crew members.

The final test was a conventional cab car led passenger consist hitting a standing locomotive led consist. The force crush characteristic measured was again very similar to the other measured characteristics. The cab car overrode the standing locomotive and crushed roughly twenty-two feet. This amount of crush would have resulted in the loss of six or seven rows of passenger seats. The coach cars following the cab car all experienced "Saw-tooth" lateral buckling and the rail rolled from beneath the passenger consist. Override of one vehicle over another is a particularly dangerous deformation mode. Very large crush distances often ensue with the potential for the loss of many lives. There was no structural damage at any of the coupled interfaces.

Current design practice results in passenger equipment in which the first car to suffer significant structural damage is likely to be the only car that suffers damage. Figure 3, a photograph of the structural damage focused on the impact equipment for the train-to-train test, confirms this observation.

Figure 3. Post-Test Photograph, Train-to-Train Test of Conventional Passenger Equipment

Figure 4 depicts the measured force crush characteristic obtained from all of the in-line conventional tests. The shape of the force crush characteristics provides insight into why crush tends to be focused at the colliding interface of conventional equipment. All the curves have an initial elevated peak at small crush distances. After the initial high peak, the load level plateaus for larger crush distances. Once the force level has surpassed the initial peak of the lead car it never rises sufficiently high again to pass crush back to other interfaces along the consist.

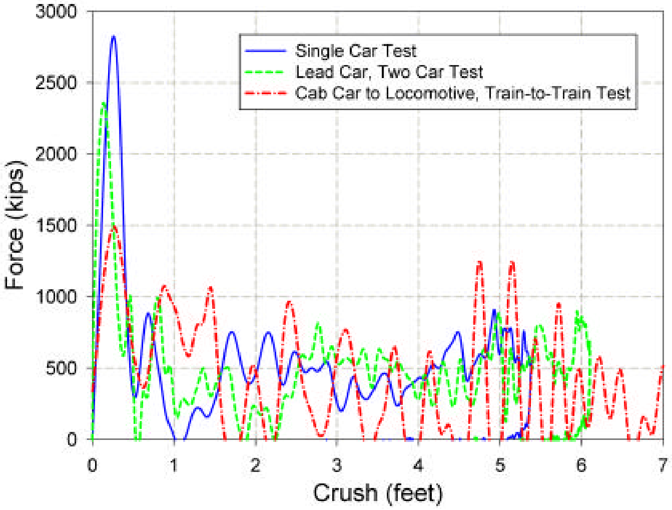


Figure 4. Measured Force Crush Characteristics from Conventional Full Scale Tests

The shape of the force crush characteristic is a consequence of the manner in which these types of cars were designed. The 800,000 lbf buff strength requirement has generated designs that have very stiff underframes. The key structural elements in the underframe that resist longitudinal loads are the draft sill/center sill and the side sills. The draft sill is usually designed with a varying cross-section. The largest opening occurs at the bell mouth of the vehicle. A smaller uniform size connects the draft sill to the center sill at the bolster of the car. Due to the need to incorporate stepwells, the side sills usually do not extend along the full length of the car but instead are discontinuous between the end of the car and the body bolster.

DEVELOPMENT AND TESTING OF A CRASH ENERGY MANAGEMENT DESIGN

Figure 5 shows a flow chart of the principal steps taken to develop the information needed to compare the crashworthiness of the CEM equipment to conventional rail passenger equipment. While the flow chart suggests linear relationships, these tasks are in fact recursive and iterative. For example, development of the design influences the design requirements.

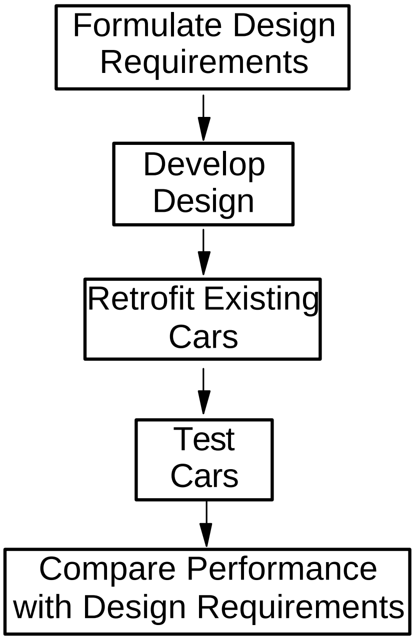


Figure 5. Flow Chart, Development and Testing of Improved Crashworthiness Design Passenger Equipment

Design Requirements

It is necessary to define a set of requirements that a crash energy management design must meet. The requirements can be broken down into three categories: crashworthiness requirements, service requirements, and fabrication requirements. A flow diagram of the interrelationship of the three categories is shown in Figure 6. Most of these requirements are the same for CEM equipment as for conventional equipment. The distinction from current practice is in the deformation requirements.

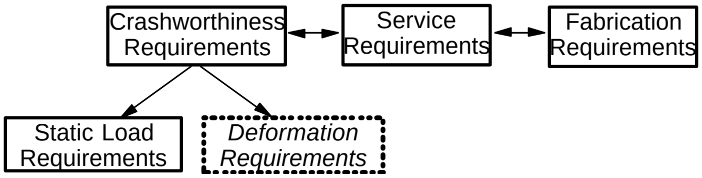


Figure 6. Flow Chart, CEM Equipment Structural Design Requirements

Service requirements for the CEM equipment are essentially the same as for conventional equipment: the ability to couple/uncouple with conventional equipment while maintaining comparable in-train buff and draft responses as well as braking performance; the design must be capable of withstanding the normal in-train buff and draft forces without pre-maturely triggering or failing due to fatigue of the new components; and the design must be able to negotiate the tightest curves that comparable conventional equipment can without interference concerns. The necessary space for all equipment that is required for regular operation of the modified vehicle must be preserved.

Fabrication requirements arise principally from desires to retrofit existing equipment and to use materials and techniques common to the rail equipment manufacturing industry. The design developed was to be retrofitted onto a pair of Budd Pioneer passenger rail vehicles.

The static load requirements are based on the APTA standards and federal regulations that are currently in place. In general the APTA standards require higher load levels than those called for in the federal regulations. These standards and regulations were used as a starting point for developing the static load requirements. Table 1 summarizes selected APTA standards and the modified static load requirements for the crush zone. The 200,000 lbf requirement on the anti-climber at full crush applies to cab cars but was deemed necessary for this coach car design to ensure that the coupled car ends remain engaged and do not experience differential vertical motions. The collision post requirements are those typically used for cab cars. In the event of override initiation, the intent is that the endframe will be strong enough to trigger the primary energy absorbers. The buff load requirement in APTA varies depending on the location in the vehicle. Any areas occupied must meet the 800,000 lbf buff strength. In unoccupied areas, the APTA standard restricts the trigger load for the primary energy absorbers to be greater than 125% of the trigger load for the pushback coupler. In addition, the minimum end compression load in unoccupied zones of the car must be greater than 50% the values of occupied areas.

Table 1. Static Load Requirements for Coach Car Crush Zone Design

Component	APTA Standard	Requirement for Crush Zone Design
Buff Strength	A load of at least 125% of the pushback coupler systems peak load applied to the line of draft with no yield. A minimum load that is 50% of the required buff load in occupied areas of the car applied on the buffer beam over an area no greater than 6 inches high by the distance between the outboard webs of the collision posts with no yield. A buff load of 800x10^3 lbf applied on the buffer beam over an area no greater than 6 inches high by the distance between the outboard webs of the collision posts with no yield.	A buff load of 800x10^3 lbf applied along the line of draft with no yield. A buff load of 800x10^3 lbf applied on the buffer beam over an area no greater than 6 inches high by the distance between the outboard webs of the collision posts with no yield.
Interlocking Anti-climber	The anti-climber must resist a vertical load of 100x10^3 lbf up or down with no yield.	A vertical 100x10^{3}lbf load in an undeformed state. A vertical 100x10^{3}lbf load during crush. A 200x10^{3}lbf load at the full crush distance.
Collision Posts	A 300x10^3 lbf load applied at the top of the underframe or at 18 inches above the deck at the ultimate strength. A 60x10^3 lbf load applied anywhere without yield.	A 500x10^3 lbf load at the floor without exceeding the ultimate shear strength. A 200x10^3 lbf load at 30 inches without exceeding the ultimate strength. A 60x10^3 lbf load applied anywhere without yield

The deformation requirements are related to the overall behavior of the crash energy management consist made up of distributed crush zones. The key requirement is that in the event of a collision between a moving cab-car led consist and a standing consist on a tangent track, no crush is allowed to occur in any occupied areas of the train. The collision energy must be absorbed through designed progressive controlled crush of specific components at the ends of each vehicle retrofitted with a crush zone. The crush zones must act in such a way that vertical and lateral motions are minimized. That is, no override and/or "Saw-tooth" buckling should occur.

These requirements are constrained by the decision to keep the crush zone within the floor plan of an existing single level car, *i.e.*, all the seat positions are preserved and the goal of doubling the maximum safe speed (the maximum collision speed for which all occupants are expected to survive) in an in-line collision of a cab car led consist and a locomotive led consist. Based on the train-to-train test of conventional equipment, the maximum safe speed for conventional equipment is 13 mph. The goal for the CEM equipment is to obtain a maximum safe speed of 25 mph for fully loaded ready to run passenger equipment involved in a train-to-train collision.

The results of simulation modeling of train collisions showed that the goal could be achieved by absorbing 2,500,000 ft-lbf in three feet of crush of the carbody [5]. Table 2 summarizes selected deformation requirements.

Table 2. Coach Car Crush Zone Deformation Requirements

Component	Requirement	Comments
Push-back Coupler	Energy absorption of 0.3x10^6 ft-lbf with sufficient stroke to allow anti-climbers to engage	Trigger loads must lie within range: 450x10^3 – 600x10^{3}lbf
Interlocking Anti-climber	No energy absorption	Resist vertical 100x10^{3}lbf in undeformed state as well as during crush. At full crush distance resist vertical 200x10^{3}lbf
Primary Energy Absorbers	A combined energy absorption of 2.0x10^6 ft-lbf with no more than 30 inches of longitudinal crush at floor level	There must be two primary energy absorbers located on each side of the centerline of the car within six feet of the end of the car
Roof Absorbers	A combined energy absorption of 0.2x10^6 ft-lbf with no more than 30 inches of longitudinal crush at roof level	Trigger load to activate crush zone must be 1.5 – 2.5 times higher than push-back coupler trigger load
Overall Crush Zone	Energy absorption of 2.5x10^6 ft-lbf with no more than 36 inches of longitudinal crush including the push back of the coupler	

In addition, the design is intended to provide different levels of performance at different speed ranges. For collisions where the closing speed is below 5 mph there should be no permanent deformation to the coupler, draft gear or any supporting structure. The intention for this requirement is that low speed impacts in yard operations should not damage the vehicles. The second collision range defined is between 5 and 15 mph where damage should be restricted to easily replaceable elements, such as the coupler, the draft gear, and any push back mechanism that may allow for energy absorption. No damage to the support structure should occur. The final collision range is between 15 and 25 mph where all permanent damage must be limited to the primary crush elements and the vehicle end areas.

Design Development

Figure 7 shows a flow chart of the principal steps taken to develop the coach car crush zone design. As part of the design development, selected components were destructively tested. The design was modified based on the results of these component tests.

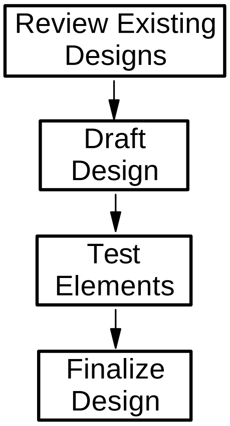


Figure 7. Flow Chart, Crush Zone Design Development

Table 3 lists some of the cars reviewed, as part of the first step in development of the design [8].

Table 3. Examples of International and Domestic Passenger Rail Vehicles with Crush Zones [8]

Vehicle	Push-back Mechanism	Anti-climbing Device	Energy Absorbers
Acela Power Car	Push-back coupler with 0.75x10^6 ft-lbf energy absorption	Ribbed plate mounted underframe within composite shell	Prismatic stainless steel absorber - 3.7x10^6 ft-lbf energy absorption
Acela Coach Car	Shear bolts with tube expansion absorber with 0.75x10^6 ft-lbf energy absorber	Tight-lock couplers with support structure	Composite cylinders, HSLA underframe, roof and side members - 3.7x10^6 ft-lbf energy absorption
TGV Duplex Intermediate Cars (France)	Conventional buffers that interlock and push-back – no energy absorption	C-channel buffers with mating protrusions with push-back shear – 0.2x10^6 ft-lbf energy absorption	HSLA underframe, roof and side members - 2.0x10^6 ft-lbf energy absorption at front and rear of lead vehicle, 0.4x10^6 ft-lbf at articulated interfaces
XTER Cab Car (France)	Shear bolts on coupler - ~0. 6x10^6 ft-lbf energy absorption -	Center ribs - 0. 5x10^6 ft-lbf energy absorption -	Steel crush zone – 2.6x10^6 ft-lbf energy absorption, with 0.6x10^6 ft-lbf at articulated interfaces
SAFETRAIN (Lead Test Vehicle) (E.U.)	Shear bolts on push-back coupler - 0.35x10^6 ft-lbf energy absorption	Ribbed plate backed by steel box absorber at buffer locations – 1.4x10^6 ft-lbf energy absorption	Steel crush zone – 1.6x10^6 ft-lbf energy absorption, with 0.5x10^6 ft-lbf at coupled interfaces
Mark I Modification (U.K.)	Push-back coupler with 45° bolted shear plane – no energy absorption	Cups-and-Cone arrangement	Cut-outs in existing steel underframe – (some energy absorption)

A feature common to many of these designs is the use of shear bolts/pins as a triggering mechanism to allow push back of sliding components. Inter-mating structures are used for the anti-climbing arrangement both with and without energy absorption capability. The use of ribbed anti-climbing structures is often employed in North American subway and transit cars. Commuter and intercity trains usually take advantage of the bending strength of couplers and the coupler support structure.

The sub-assembly tests conducted were designed to verify the performance of individual components of the complete system. These tests were conducted at a drop test facility where the impacting mass was dropped from various heights to obtain defined impact energies. Tests were conducted on the pushback coupler at two different drop heights. The first drop height was chosen to assure that premature triggering of the shear bolts did not occur. The second drop height was chosen to activate the pushback coupler and check for binding. The sub-assembly performed well. Other tests conducted at the drop tower facility were designed to check the trigger load sensitivity of the sliding sill/fixed sill assembly, and the performance of the primary energy absorbers. When acceptable results from this testing program were obtained, the design was finalized and taken to the prototype testing stage. Four crush zones were fabricated and shipped for integration onto the existing Pioneer test cars at TTC in Pueblo, CO.

The final design generated under this research program consists of three elements, a pushback coupler with some energy absorption capability, a ribbed anti-climber mounted on the end beam with no energy absorption capability, and a sliding sill/fixed sill arrangement that pushes back and loads the primary energy absorbers in the floor and the roof. Figure 8 is a schematic of the crush zone design. The roof absorbers were designed similar to a plunging system.

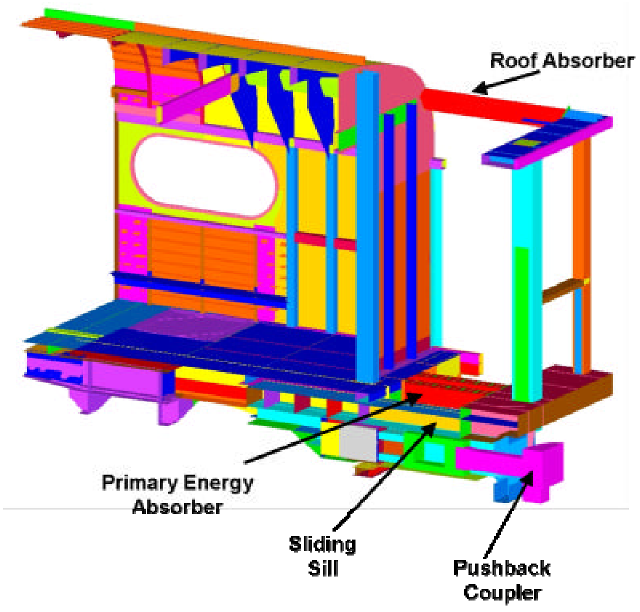


Figure 8. Schematic of Half-View of Crush Zone Design

A fixed sill/sliding sill arrangement was chosen. It is similar to designs incorporated in many North American freight cars as a means of carrying vertical, lateral, and offset longitudinal loads and bending moments during push-back. This choice eliminates the need to do additional design work to assure that otherwise plastically deforming elements are still capable of resisting such loads and moments. An additional advantage to this design is that the energy absorbing elements are passive that is they do not have to carry any service loads. This feature reduces the risk associated with failure of such elements due to fatigue prior to use in the event of a collision. An area where additional work is required before the prototype design can be used for regular service is fatigue and fracture of the shear bolts used to connect the push-back coupler to the sliding sill and the sliding sill to the fixed sill. These joints are repeatedly loaded during regular operation with buff and draft loads of relatively high magnitudes. A better characterization of the load spectrum is required to conduct a detailed fatigue analysis. Determining such a spectrum was outside the scope of the research program.

Considerable care was taken during the development of the design to assure that the pushback coupler trigger load was smaller than the trigger load for the primary energy absorbers and roof absorbers. This margin is needed to guarantee that the pushback coupler always activates prior to the sliding sill. Care was also taken to ensure that the tiered force plateaus for the coupler energy absorber and the combined primary energy and roof absorbers were sufficiently separated. This is again necessary to ensure that during pushback of the coupler the primary energy absorbers are not pre-maturely activated.

Upon initial contact during a collision, the first mechanism activated is the pushback coupler. The coupler, which is a conventional H tight-lock coupler with yoke, is designed to act elastically for very low energy impacts. If the impact event is severe enough the normal resistance in the draft gear is exhausted and the coupler “bottoms out” thereby loading a set of shear bolts that connect the pushback coupler to the sliding sill. If the eight shear bolts, which connect the pushback coupler to the sliding sill, experience a sufficiently high load they fail and allow the pushback coupler to move inward bearing against a reaction block. The reaction block is backed up by a honeycomb energy absorber that allows for an eight inch stroke. At the eight inch stroke the coupler has fully pushed back and knuckle of the coupler damages the coupler carrier and resides under the end beam. The honeycomb energy absorber was designed to absorb 300,000 ft-lbf in the eight inch stroke which equates to a mean crush load of 450,000 lbf. The honeycomb was pre-compressed to minimize the size of the initial peak load required to initiate crush.

After the pushback coupler has exhausted the honeycomb energy absorber, the two end frames of connected vehicles engage and load is transferred into the car bodies through the anti-climbers connected to the end beam into the sliding sill and through the anti-telescoping plate into the roof absorbers. If the load transferred into the carbody is sufficiently high, 12 shear bolts, which connect the sliding sill to the fixed sill fail and allow the sliding sill to push back into the fixed sill. Figure 9 is a schematic of the crush zone with the superstructure removed for clarity. The ribbed anti-climber is shown attached to the end beam between the collision posts. The pushback coupler is shown fully compressed with the energy absorber “bottomed-out”. Several cells of the primary energy absorber have collapsed. The load transferred through the primary energy absorbers is reacted through a column like structure which bears on the body bolster. In addition to this structure, load is shed through cover plates, not visible in Figure 9 but shown in Figure 8, in shear to the side sills and back into the center sill behind the bolster. The load requirement for floor level energy absorbers is 2,000,000 ft-lbf of energy in a 30 inch stroke. The mean crush load that the primary energy absorbers must control through designed progressive collapse is 800,000 lbf. This load is what the occupant volume is required to withstand elastically from the strength based requirements. The actual strength of the occupant volume before it allows severe plastic collapse is on the order of 3,000,000 lbf. This number was calculated using a finite element model [8].

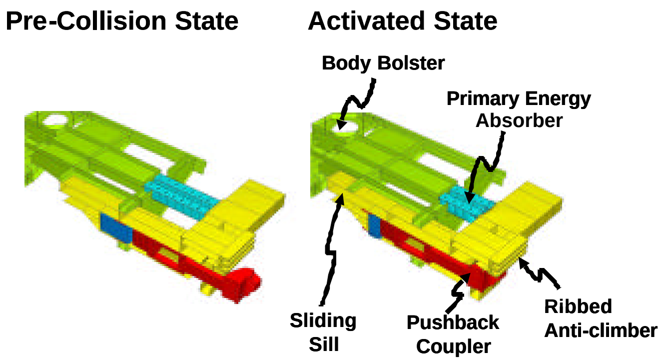


Figure 9. Schematic of Crush Zone with Superstructure Removed for Clarity

At the same time that the end beam is bearing against the primary energy absorbers at the level of the floor, the eight shear huck-bolts on each roof absorber fail and allow the inner roof absorber tube to plunge into the outer roof absorber tube. The inner roof absorber tube is filled with sectioned honeycomb energy absorbers. The end beam and the anti-telescoping plate act in unison as stiff planar surfaces that bear against the primary energy absorbers at the level of the floor and the roof absorbers at the level of the roof causing the energy absorbers to uniformly crush. The outer roof absorber is welded to the carlines and the roof sheet and the load introduced during push-back is shed in shear into the cant rail and the purlins. Special care was taken to ensure that the loads transferred through the inner tube were not high enough to crimp the tube. The roof absorbers are required to absorb 200,000 ft-lbf of energy in a 30 inch stroke. This equates to a mean crush load of 40,000 lbf apiece that must be reacted by the roof sheet, the carlines, the purlins and the cant rail.

Retrofit

Retrofitting the crush zones onto an existing older generation passenger rail vehicle was challenging. Figure 10 is a schematic of the process followed during the integration phase of the newly developed crush zone design with the existing Budd Pioneer car. The crush zones were fabricated at a separate rail shop and shipped to TTC. While the crush zones were being constructed, the Pioneer car had to be prepared for installation. A cut-out sequence was developed for use by the assembly team. The damaged ends of the cars were removed and the edges on the cut-out planes were smoothed.

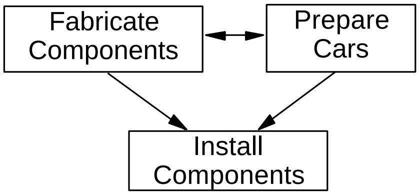


Figure 10. Flow Chart, Retrofit of Crush Zones onto Existing Conventional Cars

Figure 11 is a pre-integration photograph of one of the prepared Pioneer cars. There are a limited number of attachment points available on the existing vehicle where load is passed back into the main carbody structure. The Pioneer cars were previously used in other full-scale impact tests and had experienced some damage to the ends of the vehicle. In addition to the distortion caused by the previous testing, original fabrication tolerances on the vehicle were not very tight. Each end on both vehicles was unique due to these factors. These distortions had a large effect on the placement of new components and caused several problems. The distance from these attachment points to the end frame was sufficiently large that small errors in the placement of long structural elements were magnified. As a result of these problems, it was sometimes necessary to re-fabricate some components. Much of this work was done on-site.

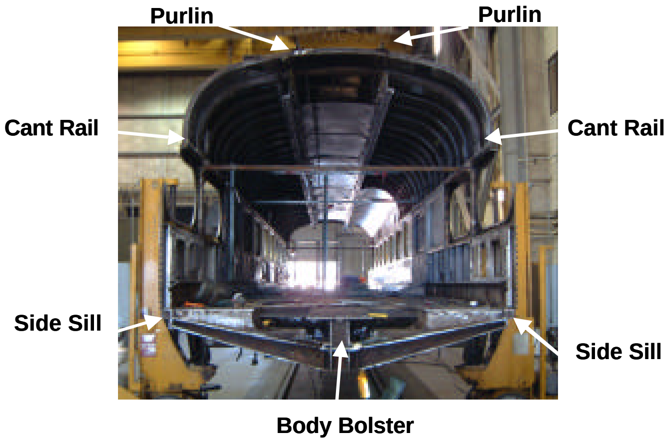


Figure 11. Pre-integration Photograph of Pioneer Car

In order for the crush zone to act as intended, it is vitally important to assure that no crush be passed back into the occupied volume. Considerable design work was required to distribute the impact load into longitudinal members capable of resisting such loads. The intention of the retrofit design was not to change existing structure on the vehicle aft of the body bolster. This goal was established to demonstrate that the prototype design could be implemented on existing equipment that meet both current federal regulations and industry standards. The four crush zones were successfully integrated onto the two Pioneer test vehicles. Figure 12 is a top view photograph of the design looking down from the test wall.

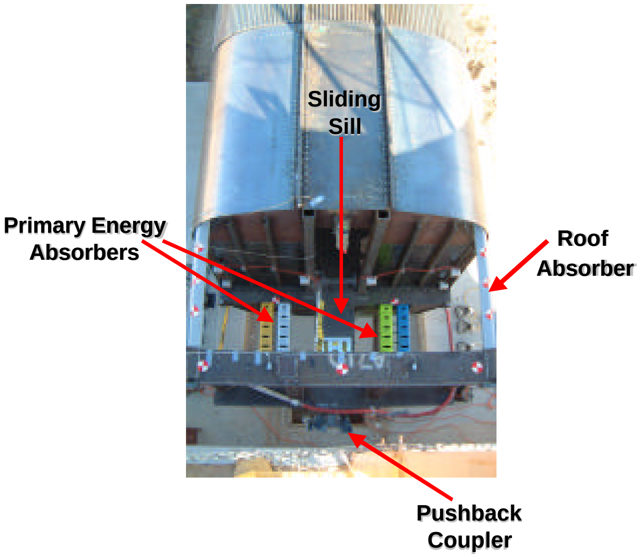


Figure 12. Top View of Finished Integrated Crush Zone Design on Pioneer Car

Full-scale Tests

Quasi-static tests were conducted to assure that the static load requirements were met and dynamic tests are being conducted to assure that the goal of doubling the maximum safe speed in an in-line collision of a cab car led consist with a locomotive led consist are met. The quasi-static and dynamic tests are shown in the flow chart in Figure 13. All of the tests have been conducted except the train-to-train test.

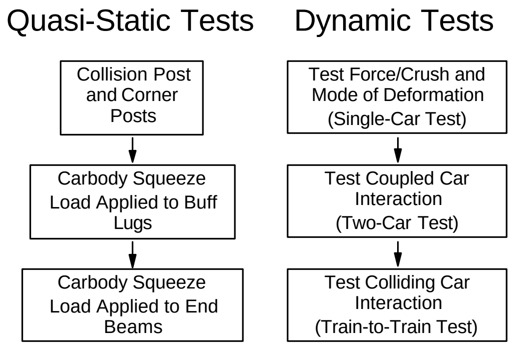


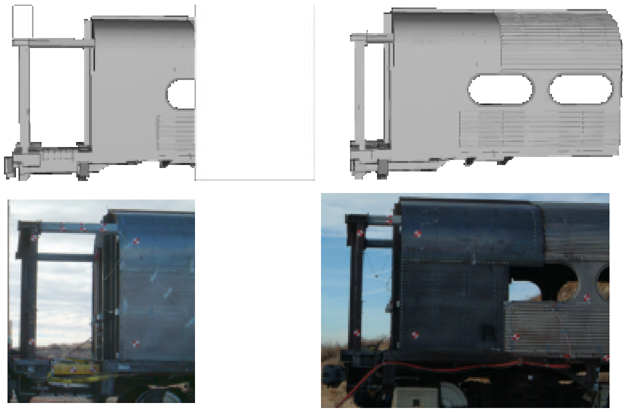
Figure 13. Flow Charts, Quasi-Static and Dynamic Fullscale Tests

Quasi-static tests were conducted on one of the retrofitted vehicles. The first quasi-static test was designed to check the ability of the push-back/draft gear system to resist an overload without pre-maturely triggering. The load was chosen based upon an interpretation of the APTA SS-C&S-034-99 Standard for testing crash energy management designs. The pushback coupler was loaded in a series of 50,000 lbf steps up to the prescribed load level of 260,000 lbf. The system remained linear elastic and the coupler did not pre-maturely trigger. The second quasi-static test was also designed to ensure that the sliding sill/fixed sill connection would not pre-maturely trigger. The end beam was loaded over an area centered 6 inches high by the outermost width of the collision posts. The load was again applied in 50,000 lbf steps up to the prescribed load of 460,000 lbf. Again the system remained linear elastic. The regular 800,000 lbf buff strength requirement in the occupied volume is met because no changes were made to the structure aft of the body bolster and the crush zone was actually designed to resist 800,000 lbf applied similarly to the 460,000 lbf load.

As discussed in the introduction, two full scale rigid barrier impact tests have been conducted on a one car retrofitted design and a two car retrofitted consist. The results from these tests are presented in [12, 13]. The discussion in this paper focuses on the overall behavior of the crush zones and not specific quantitative measures.

The crash energy management single car rigid barrier impact test was conducted on December 3, 2003 at the Transportation Technology Center in Pueblo, CO. During that test, the single car was pushed down the test track to speed, released and impacted the test wall at a nominal speed of 35 mph. The damage observed was restricted to the prescribed crush zones at the floor level and in the roof. The crush-zone performed as designed and crush was restricted to less than three feet thereby preserving the occupied volume for passengers. This result is contrasted with the conventional single car impact test where crush occurred up to just over five feet resulting in the loss of at least one row of passenger seats.

Figure 14 shows a comparison of the predicted deformations using the finite element model of the crush zone with those observed from the single CEM retrofitted Pioneer coach car test. The timing of events occurred as expected, the pushback coupler activated after the conventional draft gear “bottomed out”. The coupler pushed back the full stroke and the honeycomb energy absorber was crushed. The sliding sill was activated when the end frame next made contact with the wall and the primary energy absorbers and the roof absorbers crushed progressively and in a controlled manner. Both vertical and lateral motions of the vehicle were minimal.



Pre-Impact Post-Impact

Figure 14. Comparison of Predicted and Observed Modes of Deformation, Single-Car Impact Test of CEM Equipment

A test of two Pioneer cars modified with crush zones was conducted on February 26, 2004. During the test the two car consist was pushed down the track to speed and released at 29 mph. The crush zone at the impacting interface fully crushed and the two crush zones at the coupled car interface both activated. The cars remained in-line due to the activation of the pushback couplers, which allowed the vehicle underframes to come together as intended. The performance of the crash energy management designs was superior to that of the conventional equipment in that it better preserved occupied volume by distributing crush and it prevented excessive vertical and lateral motions from occurring. Focused crush at the impacting interface was observed at the conventional full-scale two-car rigid barrier impact test. The crush at the lead interface was just under six feet which corresponds to the loss of a single row of passenger seats. The behavior at the coupled interface was also poor. The cars experienced "Saw-tooth" lateral buckling.

Comparison of Conventional and CEM Equipment Crashworthiness Performance

The single-car test results show that the CEM equipment has an increasing force/crush characteristic, while the conventional equipment has a force/crush characteristic that decreases sharply after reaching an initial high peak. The two-car test results show that crush is distributed among the cars for CEM equipment. Crush is focused on the impacting car for conventional equipment. The two-car test results also show that coupled CEM equipment remains in-line, and does not derail. Coupled conventional equipment buckles laterally and derails. Figure 15 schematically depicts the results from a train-to-train test for both conventional and CEM modified equipment. There are significant benefits associated with incorporating CEM designs onto existing equipment. For the conventional train-to-train collision there is roughly 22 feet of crush all focused on the impacting cab car. This would result in the loss of six or seven rows of seats. In contrast, the CEM modified equipment only crush in unoccupied areas of each car. Override and lateral buckling of the CEM system is predicted not to occur. This is a substantial increase in safety.

Figure 16 is a comparison plot of the energy absorbed as a function of crush distance for both a conventional and a crash energy management front end design. Initially the conventional design, which does not exhibit controlled progressive crush, absorbs more energy than the crash energy management design. This is due to the elevated initial peak load. However after softening occurs the conventional car crushes at a relatively constant crush force at a lower force plateau.

The crash energy management system absorbs more energy in a shorter crush distance. The tiered series of force plateaus that is characteristic of the crash energy management design cause a lower initial level of energy absorption. This allows for crush to be passed back from one interface to another. The second tiered force plateau at an elevated level over a longer crush distance is where most of the energy is consumed for the crash energy management system. The key requirement for the crash energy management crush zone is that it absorbs 2,500,000 ft-lbf of energy in 3 feet of crush, to meet safe speed targets.

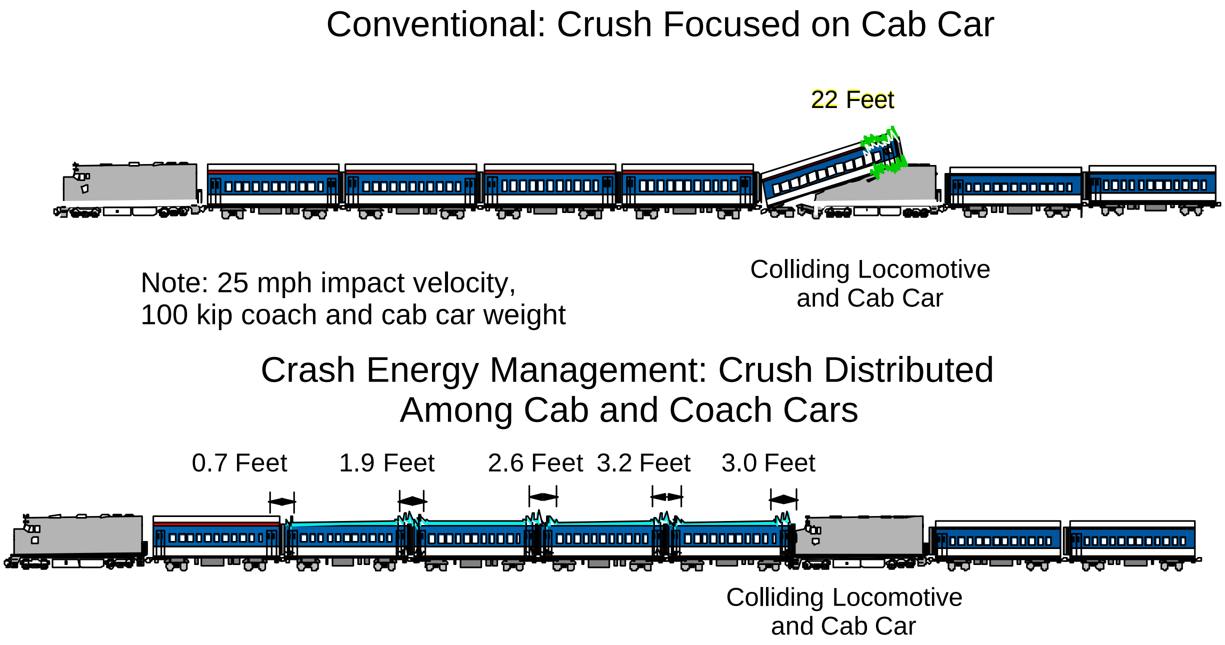


Figure 15 Schematic of Deformation Modes of Conventional and CEM Modified Train-to-Train Impacts

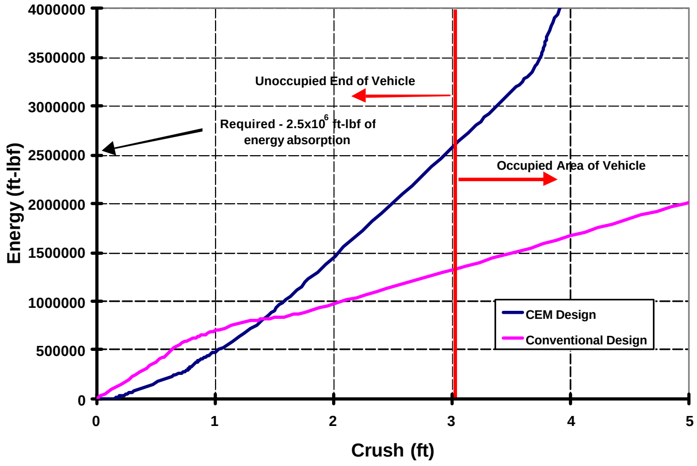


Figure 16. Conventional and CEM Design Energy Absorption with Crush Distance

DISCUSSION

One of the primary objectives of the FRA passenger equipment crashworthiness research program is to develop quantitative information about the baseline performance of conventional passenger equipment and to demonstrate the minimum achievable levels of enhancement by using either strength or performance based requirements. Under this program a crash energy management crush zone design has been developed using the concept of performance based standards. A collision scenario was defined as well as the desired outcome. A number of collision dynamic calculations were run to develop a force crush characteristic that ensures distributed crush in a consist made up of vehicles retrofitted with crush zones at each end of every car. Design requirements were drafted and preliminary designs were pursued. Of the preliminary designs generated, one concept was chosen to take to the final design stage.

The information gained from the research and testing program to date will be incorporated in the further refinement of the crush zone designs for the upcoming crash energy management train-to-train test scheduled in 2005. In order to perform the train-to-train test, one cab car and four conventional coach cars need to be retrofitted with modified crush zones. The current plan is to modify two Budd M1 coach cars as well as to repair the two Budd Pioneer coach cars already retrofitted with crush zones that have been activated. The crush zone design is currently being modified for integration into a Budd M1 cab car. The cab car design has further requirements associated with operator protection, increased corner and collision posts strength, and additional anti-climber requirements.

The results of the train-to-train test of CEM equipment are expected to show that crush can be effectively distributed among the cars of the train, preserving the space for the operator and passengers. In effect, the results of the full-scale impact tests related to train-to-train collisions are expected to show that crash energy management design can protect the operator and all the passengers for train-to-train collisions at speeds up to, and potentially beyond, 25 mph. This maximum safe speed is nearly twice the maximum safe speed of 13 mph for conventional equipment under the same collision conditions.

ACKNOWLEDGEMENTS

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

The scope of this paper ranges from collision simulations, to design development, to rail carbody construction, to full-scale testing. The authors would like to thank Dr. Ronald Mayville, of Mayville and Associates as well as Dr. Richard Stringfellow, Senior Engineer and Patricia Llana, Mechanical Engineer, Tiax, LLC, and Gabriel Amar, TRA Associates for the hard work in developing the crush zone design. The author's would like to thanks Tom Roderick, Senior Technician and Joe Hanratty, Senior Technician, TTCI for their dedicated work in integrating the crush zones onto the Pioneer cars. The authors would also like to thank Gunars Spons, Federal Railroad Administration Resident Manager at the Transportation Technology Center, for managing the full-scale test effort. Karina Jacobsen, mechanical engineer from the Volpe Center performed the pre-test simulations of the single car and two car tests of CEM equipment.

REFERENCES

[1] White, J.H., Jr., "The American Railroad Passenger Car," The Johns Hopkins University Press, 1978.

[2] National Transportation Safety Board, "Collision of Burlington Northern Santa Fe Freight Train with Metrolink [sic] Passenger Train, Placentia, California, April 23, 2002", 10/07/2003, RAR-03/04.

[3] Tyrell, D.C., Severson, K.J., Marquis, B.J., "Crashworthiness of Passenger Trains", US Department of Transportation, DOT/FRA/ORD-97/10, 1998.

[4] Romeo, D., Cassidy, R. Interim Report on Assessment of Crashworthiness of Existing Urban Rail Vehicles, DOT-TSC-681, RSPA, U.S. Department of Transportation, April 1974.

[5] Tyrell, D.C., Perlman, A.B. "Evaluation of Rail Passenger Equipment Crashworthiness Strategies," Transportation Research Record No. 1825, pp. 8-14, National Academy Press, 2003.

[6] Severson, K.J., Tyrell, D.C., Perlman, A.B., "Analysis of Collision Safety Associated with Conventional and Crash Energy Management Cars Mixed within a Consist," American Society of Mechanical Engineers, Paper No. IMECE2003-44122, November 2003.

[7] Priante, M., "Influence of Train Parameters on Crashworthiness Performance of Passenger Trains", Undergraduate Honors Thesis, Tufts University, May 2004.

[8] Mayville, R.A., Johnson, K.N., Stringfellow, R.G., Tyrell, D.C., "The Development of a Rail Passenger Coach Car Crush Zone," ASME/IEEE Paper No. ASME RTD 2003-1653, April 2003.

[9] Tyrell, D., Severson, K., Perlman, A.B., "Single Passenger Rail Car Impact Test Volume I: Overview and Selected Results," US Department of Transportation, DOT/FRA/ORD-00/02.1, March 2000.

[10] Tyrell, D., Severson, K., Zolock, J., Perlman, A.B., "Passenger Rail Two-Car Impact Test Volume I: Overview and Selected Results," US Department of Transportation, DOT/FRA/ORD-01/22.I, January 2002.

[11] Tyrell, D., "Passenger Rail Train-to-Train Impact Test Volume I: Overview and Selected Results," US Department of Transportation, DOT/FRA/ORD-03/17.I, July 2003.

[12] Jacobsen, K., Tyrell, D.C., Perlman, A.B., "Impact Test of a Crash Energy Management Rail Car," American Society of Mechanical Engineers, Paper No. RTD2004-66045, April 2004.

[13] Jacobsen, K., Tyrell, D.C., Perlman, A.B., "Impact Test of Crash Energy Management Rail Cars: Analysis of Structural Measurements," American Society of Mechanical Engineers, Paper No. IMECE2004-61252, November 2004.