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OVERVIEW OF A CRASH ENERGY MANAGEMENT SPECIFICATION FOR PASSENGER RAIL EQUIPMENT

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ABSTRACT

At the request of METROLINK, the Federal Railroad Administration (FRA), with the Federal Transit Administration and the American Public Transportation Association, formed the ad hoc Crash Energy Management Working Group in May 2005. This group developed recommendations for crush zones in passenger rail cars for METROLINK to include in its procurement specification. The Volpe Center provided the Working Group with technical information from the research on passenger rail equipment crashworthiness it is conducting for FRA. METROLINK released its specification, including the recommendations from the Working Group, on September 16, 2005, as part of an invitation for bid.

The specification includes three levels of requirements: train, car, and mechanism. The train level requirements specify a collision scenario for which there must be no intrusion into the occupied areas and limits on the relative velocities at which the operator and passenger may impact interior surfaces. The car and mechanism level requirements follow from the train level requirements. The car level requirements include specifications for a cab end crush zone capable of absorbing 3.0 million ft-lbs of energy and a non-cab end crush zone capable of absorbing 2.0 million ft-lbs. There are also specifications on the crush zone kinematics and on the target force/crush characteristics. Mechanism level requirements include specifications for the coupling mechanism, the load transfer mechanism, and the principal energy absorption mechanism. The coupling mechanism permits the coupler to push back, allowing the ends of adjacent cars to remain aligned and come together during an impact. The load transfer mechanism transmits the load from the adjacent equipment into the crush zone in a manner that allows the principal energy absorption mechanism to function as intended. The cab end load transfer mechanism can include a deformable LD that acts similarly to an automobile bumper, and resolves eccentric impact loads into loads that can be appropriately reacted by the supporting structure. The principal energy absorption mechanism is the section of the carbody structure intended to deform gracefully and to provide most of the required energy absorption.

The specification prescribes performance for the train, the cab and trailer cars, and the mechanisms. 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. This paper describes the requirements, the associated criteria, and the available evaluation techniques. The technical bases driving the need for each of the requirements are discussed.

INTRODUCTION

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 Federal Railroad Administration's (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 Crash Energy Management (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 [1] 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 Glendale Incident

Figure 1 shows a photograph of the Glendale incident. Eight of the 11 fatalities occurred in train 100, the southbound cab car led passenger train. Three of the fatalities occurred in train 901, the northbound locomotive-led passenger train. The trailing cab car from train 901 is on its side, shown in the middle right side of the photograph. This incident was investigated by several of the authors, as part of FRA's ongoing field study of injury and fatality in passenger train accidents [2].

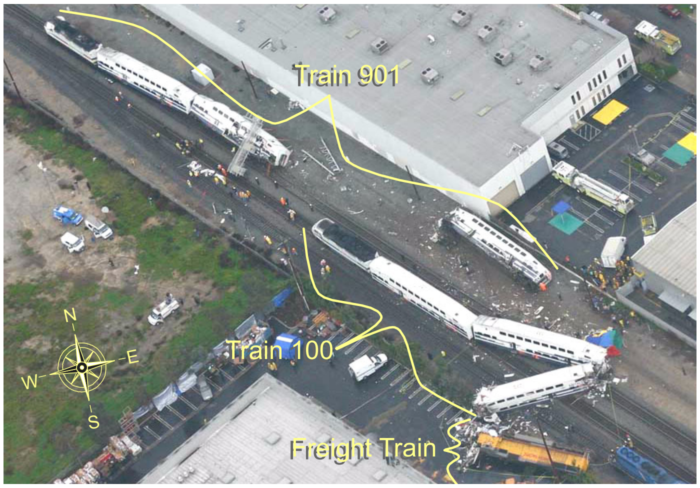


Figure 1. Aerial Photograph of Glendale Incident

Train 100, traveling south at 62 mph, collided with an SUV, which was situated perpendicular to the track with its front wheels between the rails. This impact occurred approximately 150 feet south-east of the grade crossing at Chevy Chase Drive. The SUV was lower than it would have been at a grade crossing, with the wheels of the SUV on the ties and ballast, below the running surface of the rails. This situation made it easier for some part of the SUV to get under the cab car and derail it. The Glendale incident involved three collisions:

1. The initial collision of train 100 with the SUV. Some part of the SUV–the engine block, transmission, differential, or other solid piece–became trapped under the cab car. The cab car then encountered special trackwork–switch components. The solid piece from the SUV interacted with the switch components in such a way that the front end of the cab car entered a siding. The back end of the cab car and the trailing equipment remained on the mainline track. These events led to...
2. a collision of train 100 with the freight train parked in the siding. The front of the cab car impacted a six-axle freight locomotive coupled to a second six-axle freight locomotive in turn coupled to a number of cars loaded with ballast. The impact with the freight locomotive crushed the front end of the cab car, shortening the cab car by more than 26 feet. Prior to impact with the locomotive, the cab car was skewed. The lead truck of the cab car derailed and was guided by the rails of the siding track into the freight locomotive. The rear truck of the cab car appears to have stayed on the main line track, so that the cab car was traveling with the front on one track and the back on another track. The impact with the freight locomotive appears to have caused the back of the cab car to derail and swing out further, into the right-of-way of the adjacent second main line track. These events led to …
3. a raking collision of trains 100 and 901. As the back end of train 100's cab car swung around, it impacted the side of train 901, which was traveling north at 51 mph. The back end of train 100's cab car and the front end of train 100's first trailer car first impacted the side of train 901's middle passenger car, and proceeded to rake down the side of train 901.

Passenger Rail Equipment Crashworthiness Research

FRA, with assistance from the Volpe Center, has been conducting research on passenger rail equipment crashworthiness [3]. The purpose of this research is to develop the base of technical information needed by FRA to promulgate passenger rail equipment safety regulations [4].

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 and a cab car to steel coil grade-crossing collision [5, 6, 7]. Fullscale passenger rail equipment impact tests have been conducted to allow direct comparison of conventional and alternative crashworthiness strategies [7, 8]. 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 refined using the test results and are used to extrapolate from the test results.

Structural crashworthiness strategies developed by the research include:

- cab end and non-cab end crush zones that 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 [9, 10, 11] and
- optimized cab car end frames that increase the survivable speed by 50 percent in grade-crossing collisions [12].

Occupant protection strategies developed include:

- improved workstation tables which limit abdominal loads to survivable levels [13, 14],
- optimized commuter seats which minimize head decelerations, neck loads, and chest decelerations, both forward-facing and rearward-facing [15],
- seats incorporating lap and shoulder belts to restrain intercity and commuter passengers [16], and
- inflatable structures to compartmentalize the operator [17].

CEM has been developed as a strategy for the train-to-train collision scenario. As part of CEM, sacrificial crush zones are designed into unoccupied locations in cars. These crush zones are designed to deform with a lower initial force and increased average force. With such crush zones, absorption of energy from the collision is shared by multiple cars, consequently preserving the integrity of the occupied areas [18]. Figure 2 shows the FRA prototype cab end crush zone design that was developed as part of the research. A similar design has been developed for non-cab end crush zones. The non-cab end design does not include the deformable load distributor (LD) or the operator's compartment. Cab car crush zones have been retrofitted onto Budd M1 cars, and trailer car crush zones have been retrofitted onto Budd Pioneer and M1 cars. These retrofits have not required any modification of the car structure between the body bolsters.

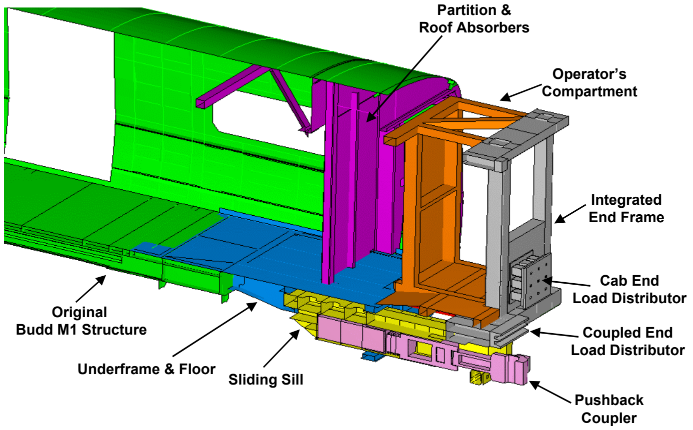


Figure 2. Cab End Crush Zone Design–Quarter Model

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 pushback coupler and the cab end LD help manage the interaction with colliding equipment. The cab end LD is deformable and acts to resolve off-axis loads from the impact into loads that can be supported by the collision and corner posts. The key elements that help manage the interactions of coupled cars are the pushback coupler and the coupled end LD. The coupled end LD acts to transmit the longitudinal collisions load between cars. For both cab and coupled ends, 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 results from the single- and two-car fullscale impact tests 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 [19]. Under the same single-car test conditions, the CEM trailer car crushed about 3 feet, preserving the occupied area, and its wheels remained on the rails [20]. 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 [21]. 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 [8].

In the train-to-train test of conventional equipment, the colliding cab car crushed by approximately 22 feet and overrode the locomotive [22]. The space for the operator's seat and for approximately 47 passenger seats was lost. 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 [9]. Structural crush will be passed back to all of the trailing car crush zones; 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.

The results of the research show that conventional equipment can protect the operator and the passengers in cab car to locomotive train-to-train collisions for impact speeds up to 13 mph, while CEM equipment with select interior modifications can protect all of the occupants for impact speeds up to 33 mph [23]. The research has also shown that CEM features can be added incrementally. A CEM cab car with conventional trailer cars can protect all of the occupants for impact speeds up to 19 mph [24]. A CEM cab car with conventional trailer cars equipped with pushback couplers can protect all of the occupants for impact speeds up to 23 mph, which is the same speed a conventional locomotive-led passenger train can protect all of its occupants in a collision with another locomotive-led train [25].

Preliminary analysis suggests that CEM could potentially prevent four of the eight fatalities that occurred in the cab car led train under collision conditions similar to those in the Glendale incident. In addition to moving the structural crush away from the occupied areas, CEM also acts to reduce the potential for lateral buckling of the train during collisions. This preliminary analysis also shows that a CEM train would not laterally buckle under collision conditions like those which led to the raking collision that occurred in the Glendale incident, potentially preventing the three fatalities that occurred on the locomotive-led train. This analysis is currently being finalized.

The modeling performed as part of the research shows the potential benefits of alternative crashworthiness strategies. The fullscale 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 are consequently developed while designing and building the test articles. This cost information is currently being used with information from an FRA field study and extrapolations from the fullscale testing to evaluate the economics of applying CEM. Preliminary results of this economic evaluation, in addition to the engineering information on CEM, were made available to the ad hoc CEM Working Group.

Ad Hoc CEM Working Group

At the request of METROLINK, FRA, with FTA and APTA, decided to form the ad hoc CEM Working Group in May 2005. Using the results of FRA's research, as well their collective experience in operating, maintaining, and constructing passenger rail equipment, this group developed recommendations for including CEM features in passenger rail equipment for METROLINK to include in its procurement specification. A symposium and four meetings were held to accomplish this goal.

The CEM Technology Transfer Symposium was held June 29 through July 1, 2005, in San Francisco. The Volpe Center presented an overview of the research, details of the effectiveness of CEM and, with support from Tiax, LLC, presented details on the design, fabrication, and testing of FRA's prototype crush zone designs. Bombardier, Kawasaki, and ARA/Indian Railways presented their capabilities as suppliers of CEM equipment. Amtrak and New Jersey Transit presented their experiences using CEM equipment in service. The ad hoc CEM Working Group was organized during the panel discussion at the end of the Symposium.

The first meeting of the Working Group was held July 27 and 28, 2005, in Los Angeles. As planned, consensus was reached on the energy absorbing capacity of the cab end and non-cab end crush zones. Details of the crush zone requirements were discussed; however, these details were not settled until subsequent meetings. The second meeting was held August 8 and 9, 2005, in Cambridge. Consensus was reached on the details of the crush zone requirements, and evaluation procedures were discussed in detail, including options for testing and analysis. The third meeting was held September 8 and 9, 2005, in Chicago. Consensus was reached on the appropriate tests and analyses needed to show compliance with the requirements.

Consensus was also reached on most of the criteria to be used in evaluating compliance. The fourth and final meeting was held in Washington, DC, on October 5, 2005. Consensus was reached on the remaining details on the evaluation criteria. Two conference calls were subsequently held, to discuss application of existing standards, such as the 800 kip buff strength requirement, to conventional equipment with pushback couplers and to discuss the allowable range for the load required to initiate pushback of the couplers.

OVERVIEW OF SPECIFICATION

Figure 3 shows a flow diagram of the specification and its relation to the design of the equipment. The specification consists of the individual requirements that prescribe the performance of the train, car, and mechanisms. Each requirement is associated with an evaluation case. Each evaluation case is associated with criteria. Testing or analysis may be required to show that the train, car, or mechanism meets the prescribed requirement. If the criteria are not met, then redesign is necessary.

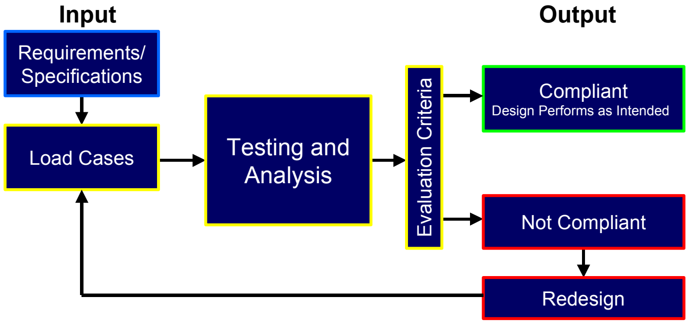


Figure 3. Flow Diagram of Specification

Table 1 lists all of the individual requirements in the specification. As noted, there are three groups of requirements: train level, car level, and mechanism level. The train level requirements specify a collision scenario for which there must be no intrusion into the occupied areas and limits on the relative velocities at which the operator and passenger may impact interior surfaces. The car and mechanism level requirements follow from the train level requirements.

The car level requirements include specifications for a crush zone at the cab end of the cab car capable of absorbing 3.0 million ft-lbs of energy and crush zones at the non-cab end of the cab car and each end of trailer cars capable of absorbing 2.0 million ft-lbs. The specification allows the operator's volume to be placed ahead of the crush zone, as it is in the FRA prototype shown in Figure 2, or placed adjacent to the passenger volume. The cab end crush zone is required to have a doorway that allows passage to an adjacent car, when coupled.

There are also specifications on the crush zone kinematics and on the target force/crush characteristics of the crush zones. There are three mechanisms required: the Coupling Mechanism (CM), the Load Transfer Mechanism (LTM), and the Principal Energy Absorption Mechanism (PEAM). The specification allows an LD to be included as part of the LTM. Mechanism level requirements include specifications for the CM, LTM, and PEAM.

Each requirement includes quantitative criteria for evaluation of compliance. Practical evaluation methodologies are available for each requirement, including non-linear large deformation finite element analysis and dynamic component tests. For the components critical to the functioning of the crush zone, some of which may be difficult to analyze, component tests are required.

The CEM requirements build on existing practice for passenger rail equipment crashworthiness. Sufficient occupant volume strength is needed to support the loads of the PEAM, and this strength is provided by the 800 kip buff strength requirement. The crush zone also needs an integrated end frame to translate the impact loads into loads that will appropriately crush the PEAM. Current corner and collision post requirements help provide the integrated end frame.

Table 1. Individual Requirements

Load Case	Analysis				Test	
	Train	Cab End	Non-Cab End	Mechanism/ Component	Quasi-Static Test	Dynamic Test
Collision Scenario	X					
PEAM Bump	X					
CM Service	X					
Ideal Impact		X	X			
LTM-Only Impact		X				
Offset Impact		X				
PEAM Support Structure		X	X			
CM Support Structure		X	X			
Retention		X	X			
Cab End LD Geometry		X				
PEAM Energy Absorption				X		X
PEAM Initiation Load				X	O	O
CM Energy Absorbed				X		X
CM Initiation Load				X	O	O
Coupled LD Deformation				X		
Cab End LD Deformation				X	O	O

Key: X–required test or analysis
O–optional quasi-static or dynamic test; one option must be selected

Train Level Requirements

There are three train-level requirements, two that are service-related and one that defines the collision scenario to be survived. These three requirements all apply to a train-to-train impact, in which a cab car with crush zones, trailed by four trailer cars with crush zones, impacts a locomotive-led train of equal mass. This impact condition is illustrated in Figure 4.

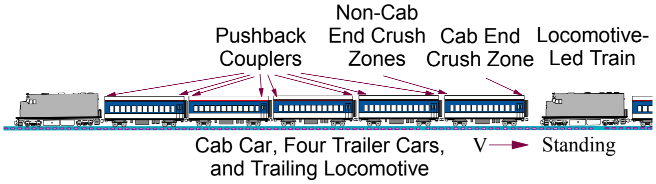


Figure 4. Train-to-train Impact Conditions

The principal CEM requirement is that, for speeds up to 25 mph, all of the occupant volume shall be preserved for an impact like the one illustrated in Figure 4. The purpose of this requirement is to assure that the crush zones and pushback couplers of the cab car and the pushback couplers of the trailer cars work together in train-to-train collision conditions as intended. In addition to preserving the occupant volume, the operator of the cab car shall not impact the interior at a relative speed greater than 22.5 mph for any interior surfaces 2 feet or less away. A Secondary Impact Velocity (SIV) of 22.5 mph is about the maximum that can be survived using compartmentalization [25]. Cab car passengers shall not impact the interior at a relative speed greater than 20 mph for any interior surfaces 2 feet or less away. An SIV of 20 mph is higher than would be experienced by passengers in a conventional cab car; passenger seats in the cab car are all required to face away from the operator's cab. The increased SIV in the CEM cab car is owing to the improved preservation of the passenger volume. Passengers in the trailing equipment shall not impact the interior at a relative speed greater than

15 mph for any interior surfaces 2 feet or less away. This SIV is comparable to those in conventional equipment under similar collision conditions [22]. The car level and mechanism level requirements follow from this train-level requirement.

One service requirement is that none of the CMs on the cab car and on the trailer cars shall activate for an impact at 5 mph or less. The second service requirement is that the PEAMs at the front and the rear of the cab car shall not activate for an impact speed of 12 mph or less. The purpose of these requirements is to ensure that impacts that may occur during service-related operations do not prematurely activate the CMs and PEAMs.

Compliance with all three of the train-level requirements can be shown using a one-dimensional lumped-parameter model [22]. Figure 5 shows the crush of the cab and non-cab end PEAMs for the collision condition illustrated in Figure 4 with an impact speed of 25 mph. Figure 6 shows the SIVs for the same case. The force/crush characteristics were developed from those of the FRA prototype designs and the conventional multi-level car. The car weights were the maximum permitted by the specification: 280 kips for the locomotive, 167 kips for the cab car, and 140 kips for the trailer car. This model represents each car with a single mass and does not calculate the SIV for the operator's compartment.

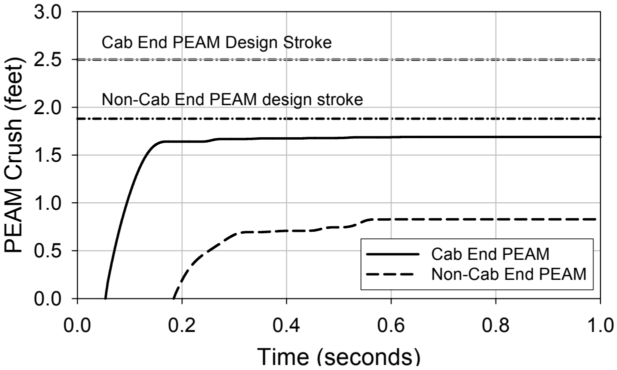


Figure 5. Example Analysis Result for Car Crush

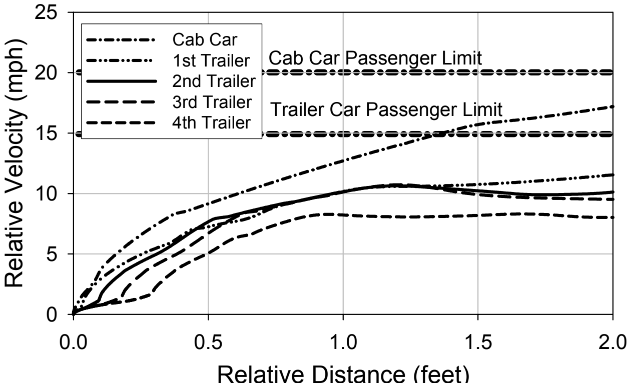


Figure 6. Example Analysis Result for SIV

The specification requires that cab cars have cab end and non-cab end crush zones and that trailer cars have non-cab end crush zones, which include PEAMs in addition to PBCs. As built, the trailer cars will be different from the trailer cars in the design scenario. Analysis results indicate that an all CEM consist can meet the scenario evaluation criteria for collision speeds up to 33 mph. This arrangement allows the suppliers to design using a scenario that was extensively discussed by the Working Group and METROLINK to have the level of crashworthiness associated with an all CEM train.

Car Level Requirements

There are seven car level requirements: three impact requirements, three static load requirements, and one geometric requirement. All of these requirements apply to the cab end crush zone design, while one dynamic and the three static load requirements apply to the non-cab end crush zone design.

Impact Requirements

Three impact cases must be evaluated: the ideal case, the LTM-only case, and the offset case. In each of these cases, the cab car impacts a rigid locomotive with a prescribed geometry. The impact speed is chosen such that there is sufficient energy to exhaust the crush zone. Figure 7 is a schematic illustration of the ideal impact case for the cab end, taken from an analysis of the cab car design developed as part of FRA research. In the ideal case, the centerlines of the cab car and locomotive couplers are aligned. For the LTM-only case, the couplers are removed, and the impact load from the locomotive is transmitted only through the LTM. For the offset case, the centerlines of the couplers are offset both vertically and laterally by 3 inches. For the non-cab end ideal impact case, the cab car impacts a flat rigid object rather than a locomotive. The LTM-only and offset cases do not apply to the non-cab end.

The impact requirements prescribe aspects of the kinematics and features of the force/crush characteristics of the cab end and non-cab end crush zones. Features of the force/crush characteristic, such as energy absorption, must fall within prescribed ranges. The crush zone kinematics must follow a prescribed sequence, the crush shall be controlled, and the operator's volume must be preserved.

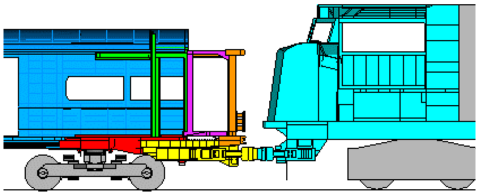


Figure 7. Schematic of Ideal Impact Case

Figure 8 is an illustration of the required kinematics of the cab end crush zone. In this sequence, the cab car and locomotive are ideally aligned. First, the couplers of the cab car and locomotive contact; then the CM initiates and absorbs energy; next the LTM is engaged; the PEAM initiates; finally, after absorbing the prescribed amount of energy, the crush zone is exhausted.

Figure 8. Illustration of Crush Zone Kinematic Sequence

Figure 9 shows an example target force/crush characteristic illustrated with the prescribed features. The specification defines the required energy absorption of the cab end and non-cab end crush zones, as well as the maximum crush strokes of the PEAMs. METROLINK has specified a minimum of 3.0 million ft-lbs energy absorption for the cab end crush zone, with a maximum PEAM stroke of 38 inches, and 2.0 million ft-lbs and 24 inches for the non-cab end. Energy absorption is the area under the entire force/crush characteristic. The supplier must define other features of the force/crush characteristic, including the initiation load range, design energy absorption, and crush stroke of the CM, as well as the initiation load range and design energy absorption of the PEAM. The specification requires that the average slope of the force crush characteristic must be zero or positive for the portion related to the PEAM. The supplier must also define the collapse load of the passenger volume.

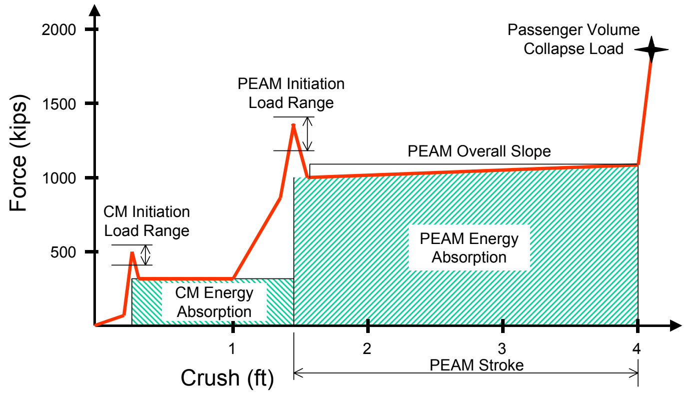


Figure 9. Example Target Force/Crush Characteristic

Figure 10 illustrates the controlled crush requirement and criteria. The top surface of the underframe shall not rise or fall more than 2 inches while the end of the car crushes. Rising or falling by more than 2 inches implies that the secondary suspension reaches its maximum displacement and that either the wheels lift from the rails or the car bottoms out on its suspension.

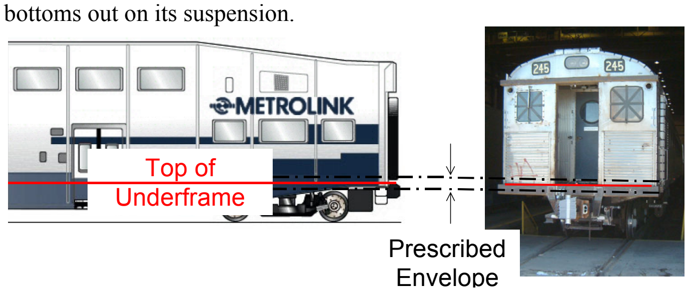


Figure 10. Illustration of Controlled Crush Requirement

Figure 11 illustrates the operator's survival volume. This requirement is similar to the requirement in the European Technical Specification for Interoperability [26]. This volume is defined relative to the seat, and the operator's console is allowed to occupy part of the volume.

Similar criteria as those illustrated in Figures 8, 9, 10, and 11 also apply to the LTM-only and offset impact evaluation cases. These cases only apply to the cab end crush zone. In the LTM-only case, no contact occurs between the cab car and locomotive couplers; hence all the load is transmitted through the LTM. For this case, the crush-zone must absorb 3.0 million ft-lbs of energy less the energy absorption capability of the CM. In the offset evaluation case, the crush-zone must absorb 3.0 million ft-lbs of energy and must meet the force/crush characteristic features, controlled crush, and operator volume criteria as illustrated in Figures 9, 10, and 11, respectively. These load cases are intended to assure that the cab end crush zone performs as desired for impact conditions that vary some amount from the ideal conditions.

Compliance with these car-level requirements may be shown with non-linear finite-element analysis [27]. Figure 7 shows a finite-element model of the ideal impact case. In this analysis, the cab car is fixed at the mid-plane, and the locomotive is impacted into the cab car at an initial speed. The locomotive is free to move. No trailing equipment is included in the model. This model was developed in the course of designing the cab car crush zone as part of FRA research. The analysis results are not sensitive to the boundary conditions, i.e., the locomotive could have been held fixed at the rear, or both the cab car and the locomotive could have been allowed full motion. The boundary conditions used in the analysis were chosen because they are computationally efficient.

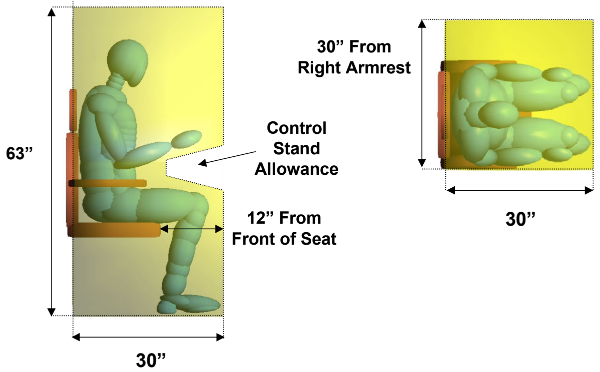


Figure 11. Operator's Survival Volume

Figure 12 shows the target force/crush characteristic and the force/crush characteristic computed with the FEA model shown in Figure 7. The total energy absorbed is 3.09 million ft-lbs. In comparison of predictions with fullscale impact test measurements, such models have shown themselves to be reliable in predicting energy absorbed. Care must be exercised in extracting such features as the PEAM initiation load. Energy absorbed can be calculated without filtering the data. Filtering is generally needed to calculate loads, but the values calculated for the loads are sensitive to the filtering. The results shown in Figure 12 were supplemented with manual calculations for the PEAM and CM trigger loads, as well as with component tests.

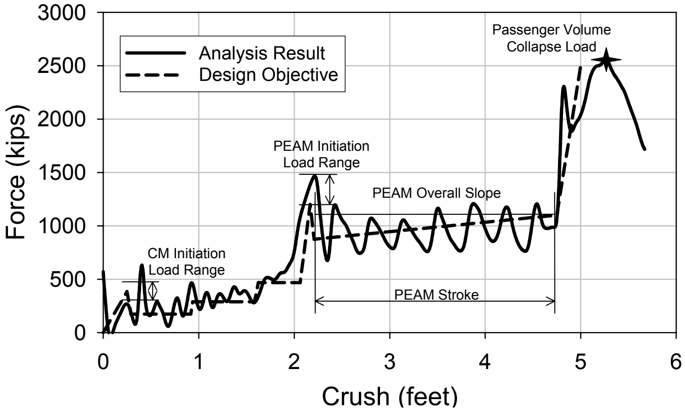
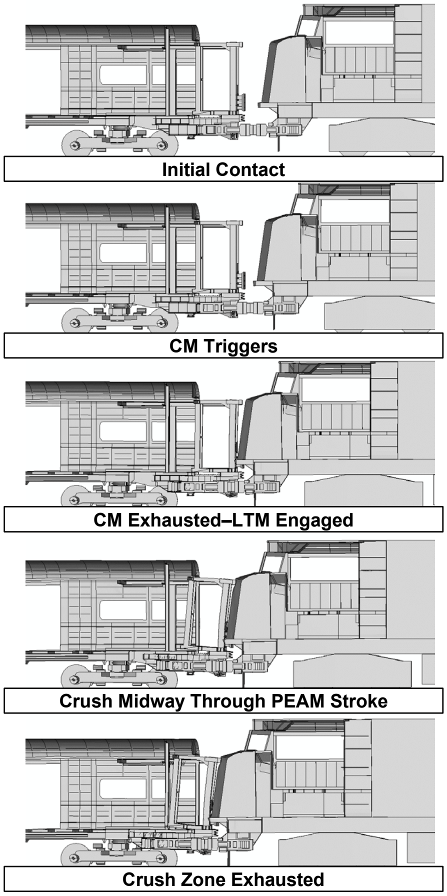


Figure 12. Example Target and Calculated Force/Crush Characteristics

Figure 13 shows the kinematics associated with the force/crush characteristic shown in Figure 12. The crush zone kinematics follow the sequence prescribed in Figure 8.


Initial Contact

CM Triggers

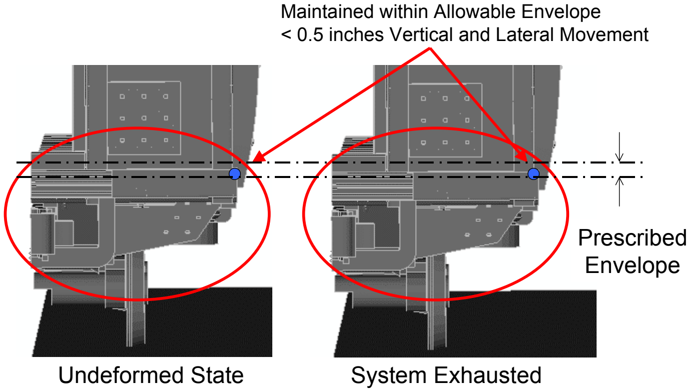
CM Exhausted–LTM Engaged

Crush Midway Through PEAM Stroke

Crush Zone Exhausted

Figure 13. Example Calculated Crush Zone Kinematics

Figure 14 shows close-up front views of the same computer simulation results shown in the top-most and bottom-most side views of Figure 13. The end beam drops slightly (less than 0.1 inches) from its initial elevation. This result is consistent with the observations made in the single-car and two-car tests of CEM equipment [8, 20].



Undeformed State System Exhausted

Figure 14. Example Calculated Controlled Crush

Figure 15 shows close-up front views of the same results shown in the top-most and bottom-most front views of Figure 13, with a box showing the locations of the operator's volume.

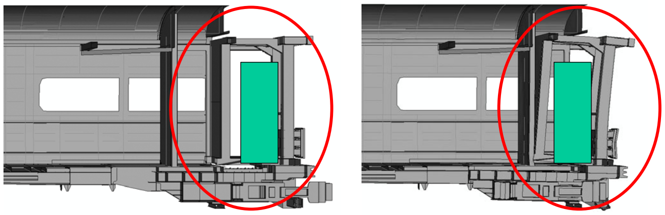

Undeformed State System Exhausted

Figure 15. Example Preservation of Operator's Volume

Static Load Requirements

The PEAM and CM support structure cases are intended to assure that support structure does not fail while these mechanisms are absorbing energy. In these evaluation cases, the car is fixed, and a static load is applied to the support structure. This load is the maximum linearized load from the PEAM or CM. No permanent deformation is the criteria for both of these cases, and both cases apply to the cab and non-cab ends. Figure 16 shows analysis results for the PEAM support structure case for FRA prototype cab car crush zone design. This is essentially the same model shown in Figure 7 but with a static loading condition. The maximum stress is below the yield stress for the material.

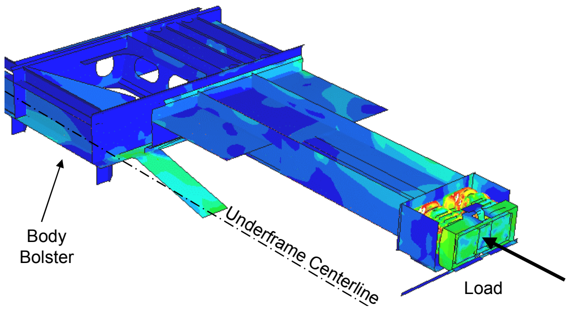


Figure 16. Example PEAM Support Structure Analysis Result

The cab and non-cab ends are also required to support a draft load after they have been fully crushed. Both crush zones shall be able to support 150 kips in draft without pulling apart. This case was analyzed for FRA's prototype CEM cab car crush zone by taking the state shown in the last frame of Figure 13 and applying a draft load to the coupler. Figure 17 shows the results of this analysis. This requirement is intended to assure that the cars remain coupled after the initial impact. Accidents have shown that separation of the cars can lead to adverse consequences.

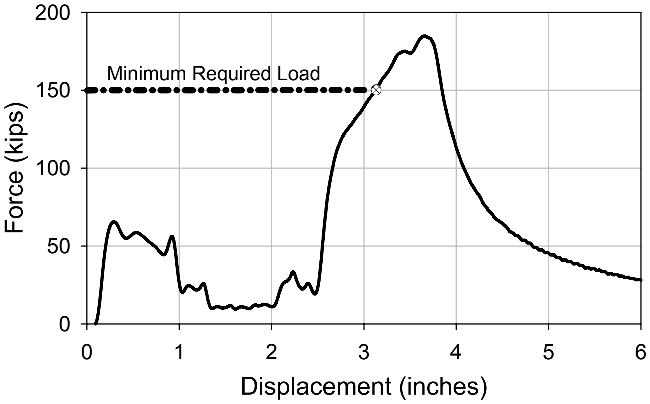


Figure 17. Example Crush Zone Retention Analysis Result

Geometric Requirements

The cab end LD is required to extend from not more than 55 inches above top of rail (TOR) to at least 75 inches above TOR. This requirement is intended to assure that the cab end LD will contact the anti-climber on a broad range of locomotives. This requirement is illustrated in Figure 18 and can be verified with the design drawings and as part of the first article inspection.

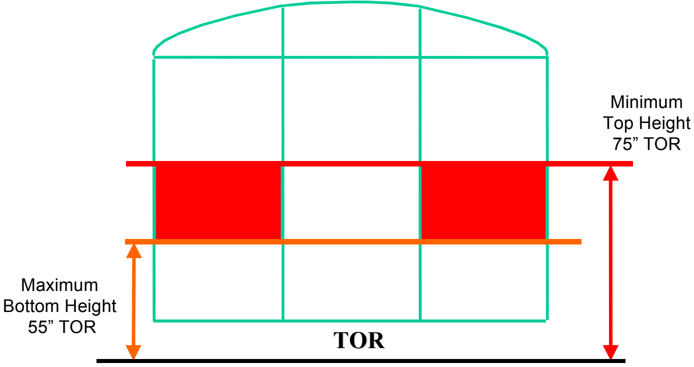


Figure 18. Illustration of Cab End LD Geometric Requirement

Mechanism Level Requirements

There are three mechanisms defined in the specification: the CM, the LTM, and the PEAM. The CM permits the coupler to push back allowing the ends of adjacent cars to remain aligned and come together during an impact. The LTM transmits the load from the adjacent equipment into the crush zone in a manner that allows the PEAM to function as intended. The LTM of the cab end can include a deformable LD that resolves eccentric impact loads into loads that can be appropriately reacted by the supporting structure. The PEAM is the section of the carbody structure intended to deform gracefully and to provide most of the required energy absorption. In addition to analyses, tests are required to show that these mechanisms meet the requisite criteria.

Coupling Mechanism

The CM is subject to two evaluation cases, one for energy absorption and one for the initiation load. As one of the first steps in designing the cab and non-cab end crush zones, the supplier must define the energy absorbing capacity of the CM. The initiation load is prescribed to be within the range from 450 to 800 kips. Component tests must be performed to show that the CM meets the criteria. Analyses must also be performed, and the results compared with the test measurements. The CM analysis can be used to help with the car-level analyses.

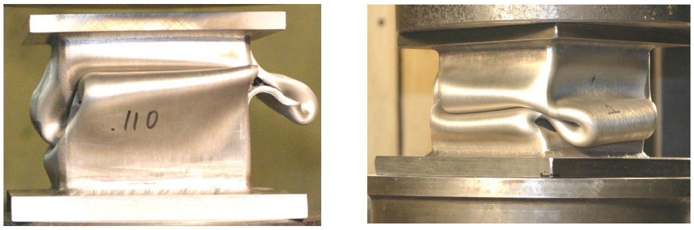
Load Transfer Mechanism

For the cab end crush zone, the functioning of the LTM is evaluated with the car-level kinematic criteria for the ideal cab car to locomotive impact, as well as with the LTM-only and offset evaluation cases; for the non-cab end crush zone, the functioning of the LTM is evaluated with the car-level kinematic criteria for the ideal non-cab end impact with a flat rigid barrier.

There are additional requirements for coupled and cab end LDs. The cab end can include a LD that can deform and resolve eccentric impact loads into loads that can be appropriately reacted by the supporting structure of the cab car. In order to preclude the formation of a ramp or vault mechanism, no material failure is desirable when the cab end LD is crushed by to its maximum stroke. The maximum stroke of the LD occurs in the LTM-only impact case. The LD requirement allows some amount of interpretation, i.e., some modest amount of material failure is acceptable if both the supplier and METROLINK agree that a ramp is not likely to form as a consequence. If material failure does occur when the LD is tested, then the supplier must perform the test a second time to show that the crush behavior of the LD is repeatable.

Material failure is also not allowed for the coupled end LD; however, this LD may act elastically or with strain substantially less than the strain associated with material failure. While the intended function of the coupled end LD is similar to the cab end LD, the impact of coupled CEM equipment is more constrained than the impact of the cab car with a locomotive. Consequently, the coupled end LD is a simpler component. The cab end is required to have a coupled end LD, so the cab car can be used as a trailer car.

Figure 19 shows the results of component tests conducted as part of the development of FRA's prototype cab car crush zone. The cab end LD includes 2½ inch square tubes, which are intended to deform on impact with a locomotive anti-climber. The tube shown on the left split during the test, while the tube on the right folded. The tube on the right is annealed, while the tube on the left is as-formed.



Material Failure **No Material Failure**

Figure 19. Example of Cab End LD Component with and without Material Failure

Principal Energy Absorption Mechanism

Requirements on the PEAM parallel the requirements on the CM. The total energy absorbing capacity of the PEAM and CM must be 3.0 million ft-lbs for the cab end and 2.0 million ft-lbs for the non-cab end. The supplier must determine how much energy the PEAM and the CM can absorb so that these totals are reached. For the PEAM, the initiation load is prescribed to be within the range from 800 to 1400 kips. The trigger load for the PEAM must be at least 200 kips greater than the trigger load for the CM. This separation in trigger loads for the PEAM and CM is required to assure the proper activation sequence of the mechanisms and distribution of crush among the cars. Component tests must be performed to show that the PEAM meets the criteria. The specification allows a single test to be performed for both energy absorption and trigger load. Analyses must also be performed and the results compared with the test measurements.

Figure 20 shows the model of the PEAM energy absorber developed for FRA's cab end and non-cab end crush zone designs. This figure shows the pre- and post-crush model. Figure 21 shows the energy absorbed as a function of crush of the energy absorber. A component test was also performed as part of the development of FRA's non-cab end crush zone design. The test measurements correspond closely to the model results. This energy absorber model was used in the development of the cab car model shown in Figure 7.

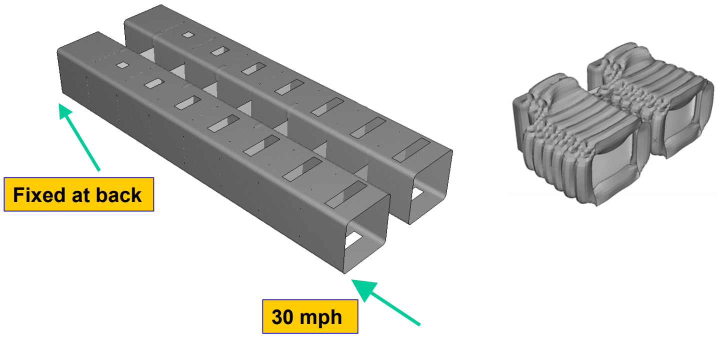


Figure 20. Example Model of PEAM Energy Absorption

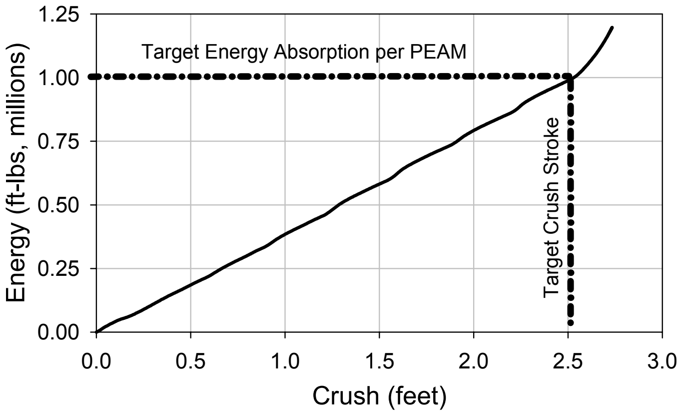


Figure 21. Example Analysis Results for PEAM Energy Absorption

Figure 22 shows the test setup for measuring the principal energy absorber trigger load. This test setup consisted of two cross heads held together with steel rods, hydraulic load rams manifolded together, load cells, and the test article. The reaction crosshead, at the end of the fixed sill portion, is not shown in the photograph. The test article included the fixed sill/sliding sill arrangement, shown as part of the crush zone illustrated in Figure 2, modified to fit the test fixture. The trigger mechanism consists of a pattern of shear bolts holding the sliding sill and fixed sill together. Once the bolts shear, the sliding sill can slide into the fixed sill. Figure 23 shows the results of the test.

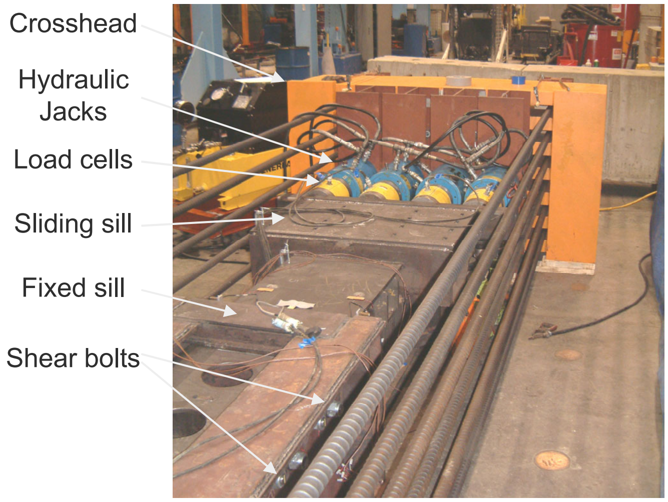


Figure 22. Example Test of PEAM Initiation Load

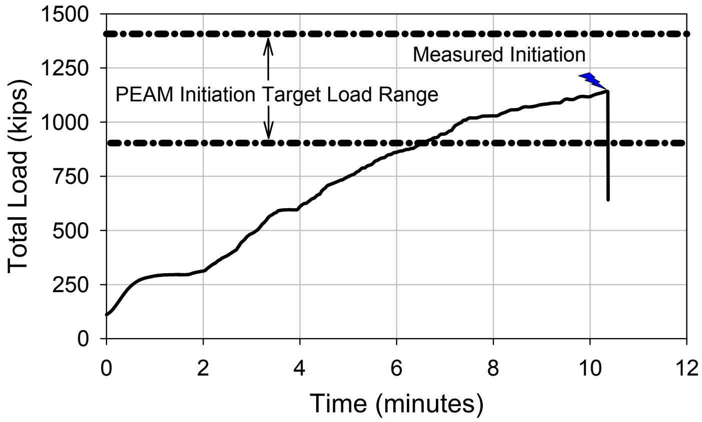


Figure 23. Example Test Results for PEAM Initiation Load

DISCUSSION

METROLINK released its specification, including the recommendations from the Working Group, on September 16, 2005 as part of an invitation for bid (IFB). Several revisions were made to the IFB. The initial IFB specified conventional trailer cars with pushback couplers. After further consideration, Metrolink revised the IFB to require full implementation of CEM on all cab and trailer cars, including crush zones at each end of every car. In an early revision, METROLINK revised the scenario to reflect the full CEM case, with an impact speed of 33 mph. After a supplier expressed concern that the Working Group had not recommended the full CEM scenario with an impact speed of 33 mph, METROLINK revised the specification back to the scenario with a CEM cab car and conventional trailer cars with pushback couplers with an impact speed of 25 mph. When built, the trailer cars will be different from those represented in this design scenario, and will have crush zones essentially identical to the crush zones at the non-cab ends of cab cars. In this way, the suppliers have a design scenario they are familiar with and METROLINK will have CEM cab and trailer cars that can protect all of the occupants in cab car to locomotive collisions at speeds up to 33 mph. The final revision was released on December 23, 2005.

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. APTA plans to wait until 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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David Solow, President, and Bill Lydon, Chief Mechanical Officer, METROLINK, requested the support in applying FRA's crashworthiness research to METROLINK's procurement. Bill Lydon coordinated the Working Group's recommendations with the procurement. Dr. Cliff Woodbury and Jeff Stastny, LTK Engineering Associates, wrote the specification language in the IFB from the Working Groups recommendations.

Jo Strang, Acting Director, Office of Research and Development, FRA, led the ad hoc CEM Working Group. Ron Hynes, Associate Director, Office of Research Demonstration, and Implementation, FTA, coordinated FTA's support and helped to lead the Working Group. Tom Peacock, Director, Technical Services, APTA, helped organize and manage the Working Group.

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