Revised Final DRAFT
For submission to the TRB Research Record

Development of a Crash Energy Management Specification for Passenger Rail Equipment

Submission Date: November 15, 2006
Word Count: 6,646

Jo Strang
Federal Railroad Administration
US Department of Transportation
112 Vermont Avenue, NW
Washington, DC 20005
Office: 202-493-6386
Fax: 202-493-6309
jo.strang@dot.gov

Ron Hynes
Federal Transit Administration
US Department of Transportation
400 7th Street, SW
Washington, DC 20590
Office: 202-366-0181
Fax: 202-366-3472
Ronald.Hynes@fta.dot.gov

Tom Peacock
American Public Transit Association
1666 K Street, N.W.
Suite 1100
Washington, DC 20006
Office: 202-496-4805
Fax: 202-496-4335
tpeacock@apta.com

Bill Lydon
METROLINK
700 South Flower Street
26th Floor
Los Angeles, CA 90017
Office: 213-452-0274
Fax: 213-452-0422
lydonb@scrra.net

Cliff Woodbury
LTK Engineering Services
100 West Butler Avenue
Ambler, PA 19002
Office: 215-542-0700
Fax: 215-654-9370
cwoodbury@ltk.com

Jeff Stastny
LTK Engineering Services
Fine Arts Building
811 West 7th Street, Suite 1200
Los Angeles, CA 90017
Office: 213-683-1495
Fax: 213-683-0503
jstastny@ltk.com

David Tyrell
Volpe National Transportation Systems Center
Research and Innovative Technology Administration
US Department of Transportation
Kendall Square
Cambridge, MA 02142
Office: 617-494-2687
Fax: 617-494-3616
Tyrell@volpe.dot.gov

ABSTRACT

At the time of the Glendale commuter train incident on January 26, 2005, in which 11 occupants were fatally injured, METROLINK was preparing to purchase new equipment. As part of its response to the incident, METROLINK decided to apply results of the Federal Railroad Administration's (FRA's) research into passenger train crashworthiness in this procurement. This paper focuses on the activities of the Federal Government and rail industry conducted in response to METROLINK's decision.

In coordination with the American Public Transportation Association (APTA), METROLINK approached FRA and the Federal Transit Administration (FTA) for support in developing a specification for Crash Energy Management (CEM) features. FRA, FTA, and APTA decided to form the ad hoc CEM Working Group. A broad-level work plan was then developed. The working group would include participants from the rail industry and government engineers. The plan included a Technology Transfer Symposium to initiate the effort and four meetings. Following this plan, a detailed technical specification was developed in just over four months.

This paper includes a summary of the research used to develop the specification, and an overview of the specification. Current practice requires that passenger rail equipment be able to support large loads without permanent deformation, but does not consider how cars behave when overloaded. CEM prescribes that car structures crush in a controlled manner and absorb energy. CEM can significantly increase crashworthiness: a cab car led train with CEM features is more crashworthy than a conventional locomotive-led train. This specification is a guide to CEM technology.

INTRODUCTION

This paper focuses on the activities of the Federal Government and rail industry that resulted in a detailed specification for Crash Energy Management (CEM) features in rail passenger equipment. The incident that led to the initiation of these activities and the formation of the working group that developed the specification are described. The paper includes a summary of the research used by the working group and a brief history of similar railroad safety working groups. Details on the makeup and meetings of the working group are included. An overview of the resulting specification is presented. The paper ends with a discussion of ongoing related activities.

The Incident

On January 26, 2005, a Los Angeles METROLINK commuter train with the cab car in the lead and traveling at 62 mph, collided with an SUV which had been purposely placed on the track by its owner approximately 150 feet from the grade crossing at Chevy Chase Drive in Glendale, California. The owner had situated the vehicle on the track with its front wheels between the rails. In this position, the SUV was lower than it would have been at a grade crossing, with the wheels of the SUV resting on the ties and ballast, well below the running surface of the rails. As the collision occurred significant parts of the SUV went under the cab car and the leading truck of the cab car derailed.

As the train continued forward with the front truck derailed, the back end of the cab car and the trailing equipment initially remained on the track. The wheels at the front of the cab car, while derailed and riding on the ties and ballast, contacted the rails of a turnout from the main track to a siding. This caused the leading end of the cab car to be diverted in the direction of the siding and follow the siding until it collided with a standing freight train. The front of the cab car impacted a six-axle freight locomotive, which had a second locomotive behind it and a number of cars loaded with ballast. The impact with the freight locomotive caused the front end of the cab car to severely deform. Because of the substantial crushing of the front end, the cab car was about 26 feet shorter after the incident.

After the impact with the freight locomotive, the back of the cab car derailed and swung out into the path of a train operating in the opposite direction on the adjacent second main track. As the back end of the cab car swung outward, it impacted the side of a passenger car and a raking collision took place with that car and the following cars of the train.

There were 11 fatalities and numerous injuries. Eight of the 11 fatalities occurred in the train that initially impacted the SUV and subsequently impacted the stationary freight locomotive. Three fatalities occurred in the train that was impacted in the side as it was operating in the opposite direction.

Railroad, Government, and Industry Response

At the time of the Glendale train incident, the Southern California Regional Rail Authority (SCRRA) was preparing to purchase new equipment for its METROLINK Trains. As part of its response, METROLINK decided to apply recent results of the Federal Railroad Administration (FRA) research into passenger train crashworthiness in its procurement. In coordination with the American Public Transportation Association (APTA), METROLINK approached the FRA.

In January 2005, Robert Jamison began acting as the Federal Railroad Administrator. Mr. Jamison continued as the Deputy Administrator for FTA, as he had done since 2002, and was keen to support safe commuter rail operations. The acting FRA Administrator immediately began working closely with David Solow, METROLINK Chief Executive Officer and FRA senior managers to assess the accident and to determine what measures could be taken to minimize casualties in such an event in the future.

When Mr. Jamison returned to FTA in June 2005 he convened discussions with METROLINK and FTA staff to determine what incentives could be provided to transit agencies to encourage CEM design in future rail car procurements. The concept was to provide initial federal assistance in the development of prototype CEM specifications, and provide incentives to transit agencies that utilize these specifications in the future.

FRA, FTA along with APTA, decided to form an ad hoc CEM Working Group, to develop recommendations for including crush zones in rail passenger cars for METROLINK to include in its procurement specification. FTA's Office of Research, Demonstration and Innovation provided specific funding for the purpose of facilitating and supporting the CEM Working Group.

BACKGROUND

The sustained existence of government/industry working groups committed to increasing railroad safety provided a seasoned pool of potential members for the ad hoc CEM working group. In order to develop the information needed by such working groups, FRA has been working with the Volpe National Transportation Systems Center (Volpe Center) to research the safety aspects of rail transportation. The results of this research include the technology for designing, building, analyzing and testing equipment with CEM features. This section summarizes the research used by the ad hoc CEM working group and describes antecedent railroad safety committee, working groups, and task forces.

Summary of Passenger Rail Equipment Crashworthiness Research

Conventional passenger rail cab and coach cars are required to support an 800 kip longitudinal static load applied at the buff stops without permanent deformation [1]. This requirement assures a minimum strength of the occupied volume of the car. The buff stops are located approximately six feet from the end of the car, and support the compressive longitudinal loads from the coupler. Meeting this requirement using conventional design practices has resulted in structures that are nearly uniform in their axial strength. These car structures are as strong at the ends as at the mid-length.

When a conventional passenger rail car is loaded longitudinally the structure of the carbody is initially very stiff. As the load is increased, deflections of the carbody remain relatively small until a critical load is reached and the carbody begins to cripple. Once crippled, its ability to further support a longitudinal load is compromised. As a result, a much lower load is required to deform the carbody longitudinally and the deflections of the carbody increase significantly. Because the longitudinal force develops in the impacting cars first, once the peak force is attained and the carbody cripples, the colliding car of a train will lose the ability to transmit significant longitudinal forces rearward to the following cars. In a collision, a colliding car that performs in this manner will singularly absorb much of the collision energy. If the collision is extreme, this situation can result in the colliding car being destroyed.

Research has shown that passenger rail equipment crashworthiness can be significantly increased if the force/crush behavior is engineered to take place in a controlled manner. Sacrificial crush zones can be designed into unoccupied locations in cars. These crush zones are designed to crush gracefully, with a lower initial force and increased average force. With such crush zones, energy absorption is shared by multiple cars during the collision, consequently preserving the integrity of the occupied areas.

The approach of including crush zones is termed CEM, and it extends from current conventional practice. The 800 kips buff strength requirement essentially prescribes the strength of the structure that supports the crush zone. By doing so, current practice controls the force required for crushing the crush zone, which in turn influences the amount of energy absorbed. The higher the buff strength, the higher the crushing force that can be supported, and the greater the energy that can be absorbed for a given crush distance.

The results from the single and two-car full-scale 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 [2]. 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 [3]. In the two-car test of conventional equipment, the 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 [4]. 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 [5]. In the train-to-train test of conventional equipment, the colliding cab car crushed by approximately 22 feet and overrode the locomotive [6]. The space for the operator's seat and for approximately 47 passenger seats was lost. During the train-to-train test of CEM equipment, at a closing speed of 31 mph, the front of the cab car crushed by approximately 3 feet [7]. The controlled deformation of the cab car prevented override. Structural crush was pushed back to all of the trailer car crush zones, and all of the crew and passenger space was preserved.

Committees, Working Groups, and Task Forces

In recent years, various government/industry committees, working groups, and task force have been formed to develop rail equipment crashworthiness regulations, standards and recommended practices.

In 1994 the FRA worked with Amtrak to develop the safety-related specifications for Amtrak's high-speed trainset, including the crashworthiness specifications. On June 7, 1995, with a mandate from Congress [8], the FRA convened a working group to draft passenger equipment regulations. This group included participants from railroads, rail labor organizations, and rail equipment suppliers. The recommendations of this working group are included in a final rule published on May 12, 1999 [1]. The FRA organized the Railway Safety Advisory Committee (RSAC) in 1996 with the purpose of developing recommended solutions to safety issues for the rail industry. The RSAC is a government/industry committee that includes all segments of the rail community – the railroads, the suppliers, and the unions [9]. The Passenger Safety Working Group was formed in 2003 and is currently developing recommendations on emergency preparedness, brakes and components, vehicle dynamic performance, and crashworthiness.

In 1998, APTA organized the Passenger Rail Equipment Safety Standards (PRESS) Committee to develop its manual of standards and recommended practices. This group included participants from the railroads, the unions, the rail equipment suppliers, and ex officio representatives from the FRA. The APTA/PRESS Manual of Standards and Recommended Practices was first published in July 1999 [10]. The construction/structural standards were revised and consolidated on January 11, 2000 [11]. The PRESS Committee and various subcommittees continue to meet as issues within their scope arise.

AD HOC CEM WORKING GROUP

The ad hoc CEM Working Group was comprised of members drawn from current and past government/industry committees, working groups, and task forces. After forming the working group, a broad-level work plan was developed by FRA, FTA, and APTA. The Plan included a Technology Transfer Symposium to initiate the effort. Four meetings of the working group were planned, with the last in mid-October 2005.

The Deputy Associate Administrator for the FRA's Office of Research and Development coordinated and scheduled the meetings and the numerous conferences calls between meetings. During the meetings and conference calls, FRA provided the use of a professional facilitator who was of great value in assisting in the resolution of divergent views. To provide answers relative to regulatory requirements, FRA provided a person with mechanical expertise from their Motive Power and Equipment Division to be present and participate at each meeting. The Volpe Center provided technical information and support to the working group. In addition, because the CEM meetings were often held near the time and location of other FRA meetings, support from additional FRA staff was frequent.

During the time that the ad hoc CEM Working Group was being assembled, FTA was in the process of formulating a cooperative agreement with APTA to support the funding of standards development for the transit industry. FTA designated a portion of those resources be used for the development of CEM specifications; APTA agreed to manage and administer the funds as part of their standards development. Because the outcome of the working group was expected to provide specifications that METROLINK could use in the procurement of railcars (and because those railcars would be purchased with FTA funds) there was frequent involvement between the FTA Office of Research, Demonstration and Innovation and FTA procurement specialists. FTA representatives attended each of the working group meetings. APTA drafted by-laws, invited participants, processed participant expense reports, advised regarding plans to incorporate the efforts of the working group in a future revision to APTA S-034

METROLINK was the near-term client of the efforts of the working group, as the resulting CEM requirements were intended for inclusion in a specification for an ongoing procurement of push-pull cab cars and trailers. LTK was the technical consultant to METROLINK responsible for preparation of the overall specification for the subject procurement of cab cars and trailers;

specific technical guidance regarding CEM and APTA S-034 drawing from experience with CEM equipment and from serving as consultant-advisor to the PRESS Construction and Structural Committee.

Railroads supplied insight regarding operations pros and cons of CEM features and designs on cars. Carbuilders reacted to proposed CEM requirements with specifics as to cost, feasibility, schedule, weight, and other issues related to design details. Suppliers provided input regarding the ability of their existing lines of equipment to meet proposed requirements, and the extent of development that would be required in cases where they felt that the level performance needed to meet the requirements was beyond the capacity of their existing lines. In some cases, the requirements were modified to minimize the need for such development. Consultants provided input based on experience with procurement of CEM rolling stock in the US and internationally, and from CEM research.

Symposium
The CEM Technology Transfer Symposium was held June 29, through July 1, 2005 in San Francisco. The FRA and FTA held the symposium to inform the car builders, consultants and railroads about the latest results of the rail equipment crashworthiness research, supplier capabilities in building equipment with CEM features, and the experience of railroads operating CEM equipment. The objective of the symposium was to share research, design and operational experience on rail passenger equipment with CEM features. The Volpe Center prepared a booklet of hard copies of all the presentations made as part of the symposium, as well as a CD containing electronic versions of the presentations and a wealth of research material on CEM.

FRA and FTA opened the symposium with an explanation that the symposium would be the first step in a process designed to produce a consensus industry specification for METROLINK to use to procure cab cars with CEM features. FRA pointed out that this specification could be broadened into an industry standard for CEM features of passenger equipment. FTA explained that they would pay the travel cost incurred by participants of the working group through a grant to be administered by APTA.

In the first session, Overview of CEM, the Volpe Center presented an overview of the research on passenger rail equipment. This overview touched on the efforts to design, build, and test passenger equipment with crush zones. The last presentation in this session discussed CEM specifications, including European specifications and how the research results could be used to develop CEM requirements for the North American passenger railroad environment. That presentation ended with the flow diagram shown in Figure 1. This flow diagram shows key elements of the specification: the scenario, the structural and occupant protection requirements, and the evaluation procedures.

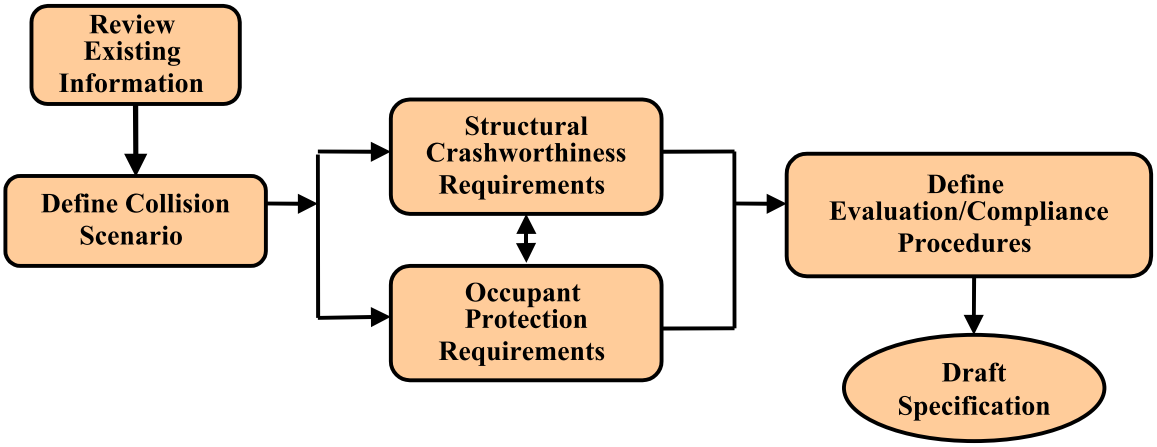

Figure 1. Flow Diagram of Specification Development

In the second session, Supplier Capabilities, Bombardier, Kawasaki, and ARA/Indian Railways presented their abilities as suppliers of CEM equipment. Bombardier presented selected CEM equipment it had built for use in Europe, and some details on the CEM features of Amtrak's Acela. Kawasaki discussed the design development of the R142 for the New York City Transit Authority. And Applied Research Associates showed some of the work it is doing with Indian Railways to modify an existing rail passenger car design to include crush zones.

Grady Cothen concluded the first day of the program by giving FRA's regulatory perspective on CEM. Mr. Cothen presented statistics comparing the fatality rates of various modes of transportation normalized per billion passenger miles traveled. The comparison showed the push mode of rail passenger service to be very safe. Regardless, its credibility has suffered from a few recent high visibility incidents. In response to these incidents, Mr. Cothen stated that FRA intends to take action to encourage the industry to improve the safety of push operations. Procuring future cab cars with CEM is one such action. He further stated that FRA would also work with passenger railroads to conduct a hazard analysis of their push-pull operations to identify operational steps that the railroad can take to reduce hazards.

The second day began with the third session, Service Experience with CEM. Amtrak presented its experience with the Acela and its CEM features. Parsons-Brinkerhoff presented New Jersey Transit's experience with the Hudson-Bergen equipment. (NJT was unable to attend due to budget constraints).

In the fourth session, the Volpe Center presented on CEM effectiveness. Presentations were made on the fullscale impact testing methodology, including the structural and occupant protection aspects [2, 3, 4, 5, 6, and 12]. Presentations also addressed alternative crashworthiness strategies [13, 14], mixing conventional and CEM equipment [15], and the influence of car weight, train make-up, and train length [16].

The fifth and final technical session, titled CEM Design, Fabrication, and Evaluation, included presentations by the Volpe Center and its contractor Tiax, LLC, and Tiax's subcontractor, TRAA. The Volpe Center summarized the design requirements for the cab end and non-cab end crush zones, Tiax reviewed the design process, and TRAA presented details of the final designs

[17, 18]. The Volpe Center gave an overview of the retrofit of the crush zones onto existing Budd M1 and Pioneer cars. Tiax presented details of the component tests, component, car, and train analyses used in the development of the designs.

The third and final day started with a question and answer session with the audience. After the questions and answers, a Panel Discussion was held, with representatives from FRA, FTA, APTA, Amtrak and METROLINK. METROLINK stated their commitment to procuring cab cars with CEM features and appealed to all the participants of the CEM Working Group to try to set aside their self-interests during this process. APTA handed out draft by-laws proposed to govern the CEM specification development process. To conserve time at the first working group meeting, APTA asked that participants come to consensus over the bylaws during the session that day. The bylaws defined consensus as a 75% super-majority based on one vote per organization. METROLINK appointed a recording secretary for configuration control of the working group work product as it evolved. The principal objectives for each of the four planned meetings were discussed and agreed upon.

Approximately 40 people signed up to participate in the working group. Overall, the working group followed the initial plan closely. Two conference calls were held after the fourth meeting to finalize details on coupler requirements and on the relation of current standards to the CEM requirements.

Three weeks before the first working group meeting, a technical specification drafted by LTK, based on Volpe Center recommendations, was e-mailed to the working group members. The combined design, fabrication, analysis, test and operations experience of the ad hoc CEM Working Group was applied to perform a thorough check on the specification. At first three meetings, the Volpe Center used presentation material to guide the technical discussions.

Meeting 1: Consensus on Energy Absorption and Discussion of Scenarios
The first meeting of the working group was held July 27 and 28, 2005 in Los Angeles at METROLINK headquarters. The target objectives for the meeting were to reach preliminary consensus on the collision scenario (or scenarios) to be designed against, to reach preliminary consensus on the energy absorption capacity of cab and non-cab end crush zones, and to discuss the detailed crush zone requirements.

After much discussion, the working group decided that specifying function, rather than components, would be more desirable. For example, instead of specifying a shearback coupler, a coupler mechanism with prescribed behavior would be specified. By describing the function, rather than the features, more flexibility would be afforded to the suppliers. Flexibility for the suppliers was one of the themes that emerged from this meeting, and continued as a theme throughout the process. Consensus was reached on the energy absorbing capacity of the cab end (3 million ft-lbs) and non-cab (2 million ft-lbs) end crush zones.

During the meeting, METROLINK described the consist for the collision scenario as a cab car with crush zones at both ends, and conventional trailer cars with pushback couplers only (no structural crush zones). In a collision with a locomotive led train, such a cab car led consist has the same crashworthy speed as a conventional locomotive led consist [14]. The crashworthy speed associated with a collision scenario is the maximum speed for which all of the train occupants would be expected to survive.

METROLINK also stated that they were open to alternative configurations of the cab car nose (or a cab end). The FRA prototype cab car places the operator's cab ahead of the crush zone. While the space for the operator can be preserved, this configuration results in a severe secondary impact environment. As a result, increased occupant protection measures, such as inflatable structures [19], are needed. Placing the operator's cab behind the crush zone greatly reduces the accelerations that would be imparted to the operator during a collision, and consequently reduces the occupant protection requirements. The working group decided that the specification should allow the supplier to choose from both options.

At this first meeting, the working group laid the groundwork for achieving focus at the second meeting. The key accomplishment of this meeting was the working group modifying the proposed framework for the specification into a framework that all the members accepted. This working group came to the second meeting well prepared to meet its goal.

Meeting 2: Consensus on Scenario and Discussion of Evaluation Procedures
The second meeting was held August 8 and 9, 2005 in Cambridge at the Volpe Center. The target objectives for the meeting were to reach consensus on the detail requirements for the crush zones and to discuss evaluation and compliance procedures, including the options for analyses and testing, as well as the criteria for each of the individual requirements.

The Volpe Center presented preliminary results of an analysis of the crush behavior of METROLINK's current multi-level equipment. These results were presented to facilitate discussions on how to specify pushback couplers for otherwise conventional equipment. There was concern expressed that conventional cars modified with pushback couplers might not have any structural components identifiable as buff stops and that applying the 800 kip buff load to the extreme ends of the cars would likely lead to permanent deformation in the area around the load application. The working group requested that the FRA Office of Safety provide a written clarification on how to apply the buff load requirement to equipment with pushback couplers. This issue continued to be discussed through the remaining meetings, and in a subsequent conference call.

The working group discussed ideal load cases for the cab and non-cab end crush zones. Consensus was quickly reached that both ends should be evaluated for ideal impacts. For the non-cab end, a rigid flat barrier was selected as the impact object. For the cab end, a rigid object with the shape of a locomotive was selected as the impact object. Working group members expressed concern that performing the offset load analyses might be time-consuming and consequently expensive. The Volpe Center and Tiax described how these cases could be analyzed with the same model developed for the in-line case with different initial conditions.

At the previous meeting, the working group had reached consensus that there would be no scenario requirement. It was pointed out that this approach would constrain the suppliers to design using the cab and non-cab end force/crush characteristics developed for the FRA's prototype crush zone designs. After discussion of simple one-dimensional lumped parameter models providing as accurate a prediction for the distribution of crush along the length of the train and the SIV as detailed Finite Element (FE) models, the working group agreed that a collision scenario should be developed.

After the meeting, the draft specification was revised by LTK and e-mailed to the working group August 26, 2005, two days before the next meeting. The Volpe Center also sent out its estimated engineering costs for developing cab end and non-cab end crush zones, and modifying a conventional car design to include a pushback coupler. The estimate was based on costs associated with the development of the FRA crush zone designs, and was put together as part of an ongoing benefit-cost analysis of CEM. The FRA provided a memo intended to clarify how the buff strength requirement would be applied to passenger equipment with pushback couplers.

Meeting 3: Consensus on Evaluation Procedures and Discussion of Criteria
The third meeting was held September 8 and 9, 2005 in Chicago at the Hilton hotel. The target objectives for the meeting were to reach consensus on the required tests and analyses, and to discuss the criteria for evaluating the results of these tests and analyses.

Based on the discussions from the previous meeting, consensus was quickly reached on the required tests and analyses. Analyses and tests are required to show that the mechanisms meet the requisite criteria. The purpose of these tests is to measure the coupling mechanism initiation load and energy absorption, the principal energy absorption mechanism initiation load and energy absorption, and to assure that any deformable elements of the cab end load transfer mechanism cannot lead to the formation of a ramp, which could promote override. The working group agreed that verification of car level and train level requirements would be by analysis alone.

Consensus was reached on nearly all of the criteria for evaluating the test and analyses results. The suggested requirement that no material be allowed for the deformable parts of the load distributor was the exception. In order to preclude the formation of a ramp or vault mechanism, no material failure is desirable when the cab end load distributor is crushed by to its maximum stroke. The concern was that this requirement was overly conservative. Eventually, the working group recommended that the load distributor requirement allow 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 with override as a likely consequence.

Much of the meeting involved detailed review and editing of the specification language. LTK walked the working group through the specification language, while the working group made recommendations for edits.

On September 15, 2005 a teleconference of interested participants was held to discuss the coupler mechanism. The conferees agreed to recommend to the working group that the range for coupler initiation loads be increased somewhat and that the minimum difference in the coupler mechanism and principal energy absorption mechanism initiations load be specified.

After the meeting, LTK revised the draft specification and e-mailed it to the working group on September 28, 2005.

Meeting 4: Consensus on Criteria and Discussions on Existing Standards
The fourth and final meeting was held in Washington, DC on October 5, 2005 at APTA headquarters. The target objectives for the meeting initially had been to reach consensus on the criteria for evaluating the load cases. Consensus had been reached on these topics at the previous meeting.

The meeting was shortened to one day, from the initially planned two days, and was used to address loose ends. The recommendations from the teleconference were discussed and accepted. No material failure as a potential criterion was revisited, but no substantive changes were made. Some modest amount of material failure is acceptable if both the supplier and METROLINK agree that the performance of the mechanism is repeatable. Some of the specification language was edited as a result of the discussions.

Buff strength was also revisited. A draft letter from the FRA had been circulated prior to the meeting, and conflicting comments had been received back from various working group members. The working group was unable to resolve the comments at this meeting. Discussions between APTA and FRA continued after the meeting, with drafts of clarifying language e-mailed to the working group by several members. On November 30, 2005 APTA sent a letter to the FRA Office of Safety requesting clarification of the issue. The FRA responded on December 12, 2005. METROLINK's procurement requires buff testing, so the efficacy of the FRA's clarification will be verified.

OVERVIEW OF CEM SPECIFICATION
The specification is written so that the requirements prescribe levels of performance for the train, the car, and the mechanisms. Each requirement includes quantitative criteria for evaluation of compliance. The working group discussed extensively various evaluation methodologies, including non-linear large deformation FE analysis and dynamic component tests, and worked to assure that there are practical evaluation methodologies available for each requirement. For the components critical to the functioning of the crush zone, some of which may be difficult to analyze, component tests are required.

Figure 2 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, analysis, or both 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.

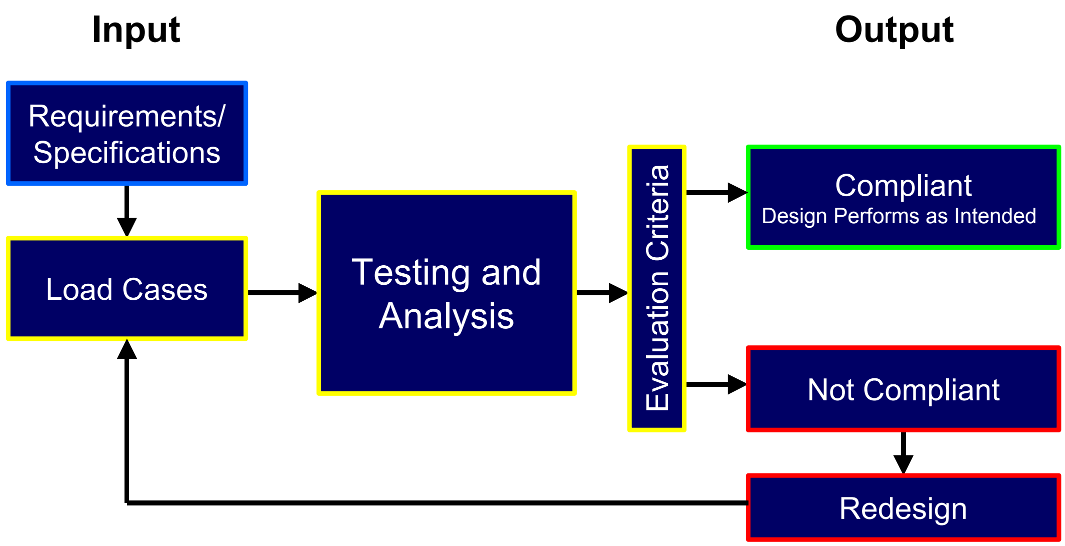

Figure 2. Flow Diagram of Specification

Table 1 lists all of the individual requirements in the specification. 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. 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 LTM of the cab end can include a deformable Load Distributor (LD) that resolves off-axis impact loads into loads that can be appropriately reacted by the supporting structure. Mechanism level requirements include specifications for the CM, LTM, LD, and PEAM.

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. The final revision was released on December 23, 2005. A more detailed overview of the final specification is described in another paper [20].

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

CONCLUSION

A specification for CEM, which requires crush zones at the unoccupied ends of passenger carrying rail equipment, has been developed by the Federal Government working with the rail industry. METROLINK, the Los Angeles commuter railroad released this specification in September 2005, as part of an invitation for bid. In May 2006, the award was made to Rotem, a division of Hyundai, which manufactures rail equipment. New equipment with the CEM features is expected to be in service in 2009.

CEM is an important addition to current practice. Current practice requires that passenger rail equipment be able to support large loads without permanent deformation or failure, but does not consider how car structures behave when overloaded. CEM prescribes how car structures behave when overloaded. CEM is able to significantly increase crashworthiness: a cab car led train with CEM features is more crashworthy than a conventional locomotive-led train.

A detailed technical specification for CEM features was developed in just over four months. This rapid development was possible because of METROLINK's commitment, the availability of well-developed technical information, the sustained existence of government/industry committees committed to increasing railroad safety, and the support of the FRA, FTA, and APTA management and representatives. METROLINK initiated the discussions with FRA, FTA, and APTA that led to the formation of the ad hoc CEM Working Group. The FRA made available the results of its research into passenger rail equipment crashworthiness, which it had been conducting to support rulemaking. This research has encompassed computer simulations showing the potential benefits of CEM, and testing which has demonstrated its effectiveness. Detailed requirements have been developed as part of designing the test articles, and fabrication of the test articles has shown CEM's practicality. The FRA and APTA have been leading various government/industry working groups since the mid-1990's. These groups have brought together the railroads, the suppliers, the unions, consultants, and government organizations to develop recommendations for specifications, standards, and regulations. The combined design experience of the industry was employed to assure that the resulting specification was practical. FRA, FTA, and APTA executives committed their agencies' full support in response to METROLINK's request. These agencies provided the leadership to the ad hoc Working Group, which allowed the rapid development of this innovative specification for improved rail passenger equipment crashworthiness.

The FRA and Volpe Center are continuing to work with METROLINK, to review the design being developed by Rotem. This review is being conducted to assure that design meets the specification, and to see if there are any aspects of the specification that need revision. The FRA and Volpe Center are also working with the APTA to start the process of developing industry standards for CEM features.

Acknowledgments
The research described in this paper was performed as part of the Equipment Safety Research Program sponsored by the Office of Research and Development of FRA. The authors would like to thank Claire Orth, Chief, Equipment and Operating Practices Division, for her support. Dr. Tom Tsai, Program Manager, leads this effort. Gunars Spons, Federal Railroad Administration Resident Manager at the Transportation Technology Center, manages the full-scale test effort. Grady Cothen, Deputy Associate Administrator for Safety Standards and Program Development, has coordinated FRA's regulations development and the passenger rail equipment crashworthiness research since the inception of this research. The authors would also like to thank the Volpe Center crashworthiness researchers, A. Benjamin Perlman, Eloy Martinez, Kristine Severson, Karina Jacobsen, Daniel Parent, Michelle Priante, and Michael Carolan for providing technical information and support to the ad hoc CEM Working Group.

References

[1] U.S. Department of Transportation, Federal Railroad Administration, "49 CFR Part 216 et al., Passenger Equipment Safety Standards; Final Rule," Federal Register, May 12, 1999.

[2] 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.

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

[4] 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.

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

[6]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.

[7] Tyrell, D. Jacobsen, K., Martinez, E., Perlman, A.B., "A Train-to-Train Impact Test of Crash Energy Management Passenger Rail Equipment: Structural Results," American Society of Mechanical Engineers, Paper No. IMECE2006-13597, November 2006.

[8] 49 United States Code 20133, Swift Rail Development Act, November 2, 1994.

[9] Cothen, G., Schulte, C., Horn, J., Tyrell, D., "Consensus Rulemaking at the Federal Railroad Administration," TR News, Transportation Research Board, Number 236, January-February 2005.

[10] American Public Transportation Association, Member Services Department, Manual of Standards and Recommended Practices for Passenger Rail Equipment, Issue of July 1, 1999.

[11] American Public Transportation Association, Member Services Department, APTA SS-C&S-034-99 Standard for the Design and Construction of Passenger Railroad Rolling Stock, Authorized January 11, 2000.

[12] Tyrell, D., Severson, K., Perlman, A.B., Brickle, B., VanIngen- Dunn, C., "Rail Passenger Equipment Crashworthiness Testing Requirements and Implementation," Rail Transportation, AmericanSociety of Mechanical Engineers, RTD-Vol. 19, 2000.

[13] 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.

[14] Jacobsen, K., Severson, K., Perlman, A.B., “Effectiveness of Alternative Rail Passenger Equipment Crashworthiness Strategies,” American Society of Mechanical Engineers, Paper No. IMECE2006-94043, April 2006.

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

[16] Priante, M., Tyrell, D., Perlman, A.B., 'The Influence of Train Type, Car Weight, and Train Length on Passenger Train Crashworthiness," American Society of Mechanical Engineers, Paper No. IMECE2005-70042, March 2005.

[17] Martinez, E., Tyrell, D., Perlman, A.B. , "Development of Crash Energy Management Designs for Existing Passenger Rail Vehicles," American Society of Mechanical Engineers, Paper No. IMECE2004-61601, November 2004.

[18] Martinez, E., Tyrell, D., Rancatore, R., Stringfellow, R., Amar, G., "A Crush Zone Design for An Existing Passenger Rail Cab Car," American Society of Mechanical Engineers, Paper No. IMECE2005- 82769, November 2005.

[19] Zolock, J., Tyrell, D., "Locomotive Cab Occupant Protection," American Society of Mechanical Engineers, Paper No. IMECE2003-44121, November 2003.

[20] Tyrell, D., Martinez, E., Severson, K., Jacobsen, K., Parent, D., Priante, M., Perlman, A.B., “Overview of a Crash Energy Management Specification for Passenger Rail Equipment,” American Society of Mechanical Engineers, Paper No. IMECE2006-94044, April 2006.