Photo: Metrolink

The Metrolink train accident in Glendale, California, in 2005 involved three trains and resulted in 11 fatalities and many injuries.

Railroads and Research
Sharing Track

Crash Energy Management

An Overview of Federal Railroad Administration Research

DAVID TYRELL AND JEFF GORDON

Tyrell is Senior Technical Advisor, Structures and Dynamics Division, Volpe National Transportation Systems Center, Cambridge, Massachusetts, and Gordon is Program Manager, Passenger Equipment Safety Research, Office of Research and Development, Federal Railroad Administration, Washington, D.C.

A crashworthy vehicle preserves space for the occupant to ride out a collision and limits the forces imparted to the occupant to survivable levels. The foundation for crashworthiness is achieved by designing and fabricating a strong principal car body structure within the limits of space and weight.

Crash energy management (CEM) is a design technique that enhances crashworthiness. CEM seeks to control the load path into the car body structure and to absorb the energy with components that are outside the occupied volume. CEM is commonly understood in the context of automobile designs that incorporate "crumple zones" and passive safety features—such as seat belts—to protect occupants. Passenger rail car construction has adopted these concepts, primarily as a result of European practice. Crashworthy designs incorporating CEM can be accomplished with computer-aided engineering.

For more than 100 years, conventionally designed car bodies have been built to support high loads without sustaining damage. This approach offers advantages, such as ease of design and demonstra-

Photo: FRA

A frame from the conventional train-to-train impact test captures the moment of override.

tion of compliance, but has a limitation—only one car may crush and absorb energy in a train-to-train collision.

Conventional crashworthy designs can be accomplished with straightforward calculations. Compliance can be demonstrated by applying a high load to a car body and carefully inspecting the car body to make sure it looks the same after the test as it did before the test. Because only one car may crush in a collision, the crush can be extensive, and occupied volume may be lost.

Crashworthiness Research

For nearly 20 years, the Office of Research and Development of the Federal Railroad Administration (FRA) has been investigating crashworthiness strategies that will ensure the preservation of occupied space and limit the severity of the secondary impact environment to which the occupants are exposed. One effective crashworthiness strategy is to build car body end structures that systematically collapse when overloaded. CEM strategies have improved the performance of freight locomotives (*1*), tank cars carrying hazardous materials (*2*), and passenger trains (*3*) in accidents.

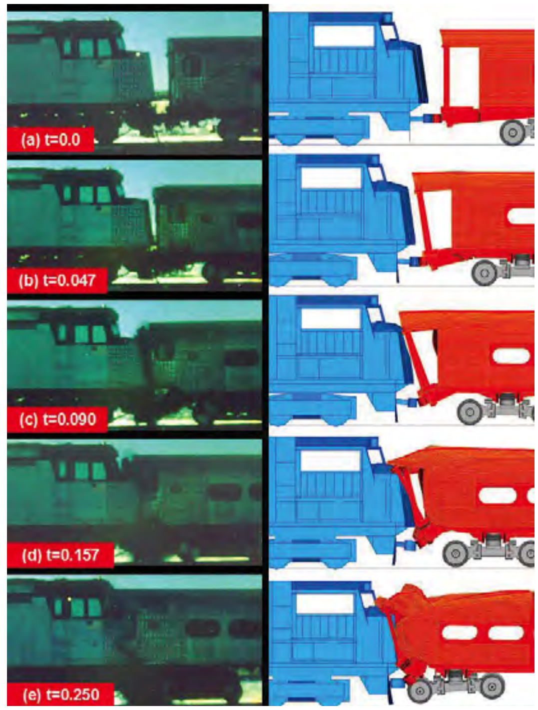
The crashworthiness research by FRA's Office of Research and Development assesses the likelihood and extent of damage from accidents and develops accident scenarios. Safety strategies to mitigate the consequences of the scenarios—including the development of technologies to improve occupied volume preservation, injury prevention, fuel containment, and glazing impact resistance—are considered, analyzed, and tested. This research produces the information to understand and apply the technology to the rail industry. The information may be used to engineer equipment, verify performance, inform policy decisions, and support standards development.

From 1999 to 2005, FRA conducted a series of six impact tests to assess the crashworthiness of rail passenger equipment, both conventional and with CEM features. The CEM designs included energy-absorbing crush zones, located at the ends of each car. The results showed that CEM features can improve crashworthiness significantly. Full participation by the rail industry contributed to the success of these tests.

Implementing the Results

The Los Angeles commuter railroad Metrolink has used the findings from the impact tests to develop specifications for the crashworthiness features of new equipment. The research also has helped lay the technical foundation for assessing the crashworthiness and occupant protection performance of alternatively designed train sets for Tier I passenger service, which does not exceed 125 mph (*4*). In addition, the results have assisted FRA's Railroad Safety Advisory Committee (RSAC) in developing recommended crashworthiness requirements for high-speed trains (*5*).

New equipment specifications increasingly are incorporating CEM, as evidenced by a suite of specifications developed for the next generation of passenger equipment. For example, the procurement of a fleet of bilevel cars for California and the Midwest, now under way, specifies CEM standards.



A crash energy management (CEM) impact test sequence shows car body end structures that systematically collapse when overloaded, limiting the secondary impact of the crash.

Photo: Don Barrett

Metrolink and other rail agencies are incorporating CEM in new equipment specifications.

Photo: Volpe Center

An April 2002 crash in Placentia, California.

Stakeholder Involvement

Government and industry working groups are committed to increasing railroad safety. Some of these groups are government-led, such as the RSAC (*6*); some are industry-led, such as the American Public Transportation Association's (APTA's) Passenger Rail Equipment Safety Standards Committee[1] (PRESS); and others are jointly led, such as the Passenger Rail Equipment and Improvement Act Section 305 Next-Generation Corridor Equipment Pool Committee.[2]

Whatever their makeup, these groups include the participation of all interested stakeholders: railroads, suppliers, labor, government agencies, and consultants. The groups address all aspects of railroad safety, including equipment safety, track safety, and operating practices, and have helped develop FRA's passenger equipment safety standards (*7*), FRA's locomotive crashworthiness standards (*8*), the Association of American Railroads' locomotive crashworthiness standards,[3] FRA's cab car end frame requirement (*9*), and APTA's standard for the design and construction of passenger railroad rolling stock.[4]

A timeline for the formation of the various working groups, along with major passenger train accidents and related crashworthiness research, is shown on page 8. Accident investigations inform the research, and the working groups apply the results to develop regulations, standards, and specifications. The new requirements in turn influence the next generation of rail equipment.

Four-Phase Approach

The approach to research and the application of results consists of four phases, illustrated in Figure 1 (page 7):

1. Accident investigations assemble a sequence of events leading to injury or fatality.
2. The equipment performance is analyzed, and

[1] www.aptastandards.com/StandardsPrograms/PRESS StandardsProgram/tabid/59/language/en-US/Default.aspx.
[2] www.ngec305.org.

[3] AAR S-580, December 2004, revised 2008.
[4] www.aptastandards.com/portals/0/PRESS_pdfs/ Construcstruct/construcstruct%20reaffirm/ APTA%20SS-CS-034-99%20Rev%202-Approved.pdf.

Photo: Volpe Center

Accident investigators on scene at a 2008 rail accident in Chatsworth, California. Research and application of results progress through four phases: accident investigation; equipment analysis and design testing; development of specifications and standards; and improved equipment design.

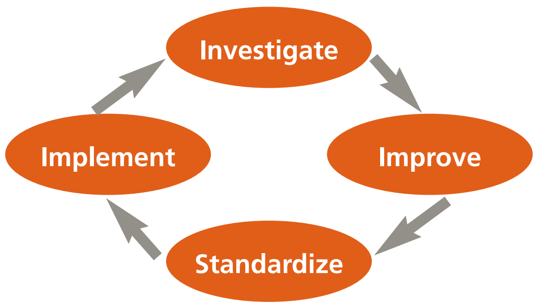


FIGURE 1 Approach to engineering research on rail equipment crashworthiness.

potential improvements are explored. Conventional and improved designs are tested, and the results are compared.

3. Specifications and standards are developed from the results of the accident investigations, analyses, and tests.

4. Improved equipment is designed according to the evolving standards and is introduced into service.

As technological advances show promise for improved performance, the phases can proceed in an evolutionary fashion, with continuous research leading to continuously improving standards and safer designs.

CEM Research Participants

The CEM research demonstrates FRA's work to engage the full spectrum of stakeholders to ensure the successful implementation of findings:

- ◆ APTA's PRESS Committee coordinated industry participation, including passenger railroad operators, suppliers, labor organizations, and consultants to assist FRA in the planning and conduct of the impact test program. The PRESS Construction and Structural Subcommittee acted as a board of directors for the tests.
- ◆ Southeastern Pennsylvania Transportation Authority, the Philadelphia commuter railroad; Long Island Railroad, one of the New York City–area commuter railroads; and Amtrak provided the cars and locomotives for testing.
- ◆ Bombardier and ElectroMotive Diesel provided structural information for the cars and locomotives.
- ◆ Tiax, with Taylor Raynauld Amar and Associates, consultants to FRA and the Volpe Center, designed the detailed CEM modifications to the conventional equipment.
- ◆ Transportation Technology Center, Inc., under contract to FRA, performed the tests.
- ◆ Under the sponsorship of FRA, the Volpe Center designed the tests and oversaw the engineering.

Photo: Volpe Center

The six full-scale tests consisted of three tests each of conventional and of CEM cars: a single car into fixed barrier (*conventional, shown*), two coupled cars into a fixed barrier, and one train into another.

Full-Scale Tests

Six tests were conducted to measure crashworthiness performance—three kinds of tests each for conventional equipment and equipment incorporating CEM features (*10*):

1. The impact of a single car into a fixed barrier,
2. The impact of two coupled cars into a fixed barrier, and
3. The collision of a train led by a cab car into a standing conventional locomotive-led train.

The single-car test recorded the force required to reduce the length of the passenger car, as well as the changes in the geometry of the car as its length was reduced. The two-car test added information about the interaction of coupled passenger cars. The train-to-train test provided information about the interaction of colliding cars, as a passenger car with an operator's control stand—that is, a cab car–led train—collided with a locomotive-led train at 30 mph.

Cars used in CEM tests were modified to include crush zones and bolsters on the ends.

Photo: Volpe Center


In tests of a single, conventional rail car crashing into a fixed barrier, the car body crippled haphazardly (*left*). The CEM equipment systematically absorbed the energy from the impact (*right*).

For the CEM tests, cars used in the conventional tests were modified to include crush zones on the ends (*11*). The center portions of the cars, between the body bolsters, were not modified, so that the strength of the primary structures remained unchanged.

Test Results

In the single-car test of conventional equipment, the car body crippled haphazardly when the peak force was reached (*12*). In the single-car test of CEM equipment, the crush zone systematically absorbed energy (*13*). The wheels remained on the track during the single-car test of CEM equipment, but the lead truck derailed during the single-car test of conventional equipment.

Timeline of Working Group Formation, Significant Accidents, and Related FRA Research and Development Activities

March 15, 1999	Bourbonnais, Illinois, passenger train–truck collision
May 12, 1999	Passenger Equipment Safety Standards Final Rule published
November 16, 1999	Conventional design single-car impact test
April 4, 2000	Conventional design two-car impact test
January 31, 2002	Conventional design train impact test
April 23, 2002	Placentia, California, train collision
2003	FRA RSAC Crashworthiness–Glazing Task Force
December 3, 2003	CEM single-car impact test
February 26, 2004	CEM two-car impact test
2005	FRA–Federal Transit Administration–American Public Transportation Association Ad Hoc CEM Working Group
January 26, 2005	Glendale, California, passenger train crash
September 17, 2005	Chicago, Illinois, passenger train derailment
March 23, 2006	CEM train impact test
2008	Waiver requests: Caltrain 2025, California High-Speed Train Project, Dallas Area Rapid Transit, and others
September 12, 2008	Chatsworth, California, train collision

In the two-car test of conventional equipment, the lead car crushed in essentially the same way as the conventional car in the single-car test; the trailing car suffered little structural damage (*14*). In the two-car test of CEM equipment, the forward and rear crush zones of the lead car and the forward crush zone of the trailing car were activated; the cars remained in line, and the loads transmitted between the cars remained aligned with the stronger structural elements (*15*).

In the train-to-train test of conventional equipment, the front third of the colliding cab car was crushed, with little damage to any of the other equipment. In the conventional train-to-train test, the cab car lost the space for the operator and 47 passengers (*16*). For the CEM equipment, the impacting CEM cab car and conventional locomotive remained in-line and engaged. The crush was distributed among all of the cars of the passenger train. The CEM train-to-train test preserved the entire occupied volume for the passengers and crew (*17*).

CEM Specification

At the time of the Glendale incident in January 2005, Metrolink was preparing to purchase new equipment. The accident involved three trains, resulted in 11 fatalities and many serious injuries, and was investigated in an ongoing FRA field study of occupant injury in passenger train collisions and derailments (*18*).

Metrolink sought to apply results from the FRA crashworthiness research in the procurement. APTA and Metrolink collaborated with FRA and the Federal Transit Administration (FTA) to form an ad hoc CEM Working Group of stakeholders in May 2005.

In approximately four months, the group developed a detailed specification for a CEM cab car–led train that was as crashworthy as a conventional locomotive-led train (*19*). Metrolink's commitment, the availability of well-developed technical information, the sustained commitment to railroad safety by government and industry groups, and the support of FRA, FTA, and APTA management and representatives contributed to this success.

The specification prescribes performance requirements for the train, the cab, the trailer cars, and the CEM mechanisms. Each requirement includes quantitative criteria for evaluating compliance. Components critical to the functioning of the crush zone underwent destructive testing, to ensure that the performance requirements were achieved.

Metrolink released the specification, including the CEM recommendations, on September 16, 2005, as part of an invitation for bids. The contract for the equipment manufacturing was awarded to Rotem, a division of Hyundai, now Hyundai Rotem Company. Rotem developed a shaped-nose, CEM design for the new Metrolink cab cars (see photograph, page 10). This equipment went into service in December 2010.

Ongoing Activities

Until recently, the rail industry had relied on nondestructive tests and manual calculations to demonstrate crashworthy designs that complied with regulations. Classical engineering beam and elastic analyses have assured that the structures can support high loads without damage or "permanent deformation."

Much of the technology that was developed from the test program has relied on computer simulations and destructive testing of critical components to demonstrate performance. Uniform practices are being developed for applying computer simulations, to assure a shared understanding by the railroads, rail equipment suppliers, and FRA. The RSAC's Engineering Task Force is performing much of the work for establishing industry best practices.

Related FRA research has addressed occupied volume integrity (*20*), to facilitate alternatives to the longstanding end strength requirement of 800,000 lb for conventional equipment (*4*). Other research includes the development of prototype CEM components for locomotives (*1*). CEM research findings also have benefited FRA research to improve the integrity of tank cars carrying hazardous materials (*2*).

PHOTO: VOLPE CENTER

In the coupled-car tests of conventional equipment, the lead car crumpled while the trailing car stayed mostly intact; the load path was distorted.

The colliding CEM car and conventional locomotive remained inline and engaged in train-to-train impact tests.

Metrolink's new cars feature a shaped-nose, CEM design, manufactured by Hyundai Rotem Company.

FRA and industry are working together to address and cope with a range of safety concerns. The CEM tests and the application of the research results to improve railroad safety exemplify FRA's successful influence on railroad safety culture.

References

1. Llana, P., and R. Stringfellow. *Preliminary Development of Locomotive Crashworthy Components*. Paper No. JRC2011-56104, American Society of Mechanical Engineers, March 2011.
2. Jeong, D. Y., D. C. Tyrell, M. E. Carolan, and A. B. Perlman. *Improved Tank Car Development: Ongoing Studies on Sandwich Structures*. Paper No. JRC2009-63025, American Society of Mechanical Engineers, March 2009.
3. Jacobsen, K. *Collision Dynamics Modeling of Crash Energy Management Passenger Rail Equipment*. Master's thesis. Tufts University, January 2008.
4. *Technical Criteria and Procedures for Evaluating the Crashworthiness and Occupant Protection Performance of Alternatively-Designed Passenger Rail Equipment for Use in Tier I Service*. DOT/FRA/ORD-11/22. Federal Railroad Administration, U.S. Department of Transportation, October 2011.
5. Docket No. FRA–2000–7257; Notice No. 71, Railroad Safety Advisory Committee (RSAC) Working Group Activity Update. *Federal Register,* Vol. 77, No. 184, September 21, 2012.
6. Docket No. RSAC–96–1, Railroad Safety Advisory Committee Establishment. *Federal Register*, Vol. 61, No. 48, March 11, 1996.
7. 49 CFR Part 238, Passenger Equipment Safety Standards: Final Rule. *Federal Register*, Vol. 64, No. 91, May 12, 1999.
8. 49 CFR Parts 229 and 238, Locomotive Crashworthiness: Final Rule. *Federal Register*, Vol. 71, No. 124, June 28, 2006.
9. 49 CFR Appendix F to Part 238, Alternative Dynamic Performance Requirements for Front End Structures of Cab Cars and MU Locomotives. *Federal Register*, Vol. 75, No. 5, January 8, 2010.
10. Tyrell, D., K. Severson, A. B. Perlman, B. Brickle, and C. VanIngen-Dunn. Rail Passenger Equipment Crashworthiness Testing Requirements and Implementation. *Rail Transportation 2000*, Vol. 19, 2000.
11. Mayville, R. A., K. N. Johnson, R. G. Stringfellow, and D. C. Tyrell. *The Development of a Rail Passenger Coach Car Crush Zone*. Paper No. JRC2003-1653, American Society of Mechanical Engineers, April 2003.
12. Tyrell, D., K. Severson, and A. B. Perlman. *Single Passenger Rail Car Impact Test, Volume I: Overview and Selected Results*. DOT/FRA/ORD-00/02.1. Federal Railroad Administration, U.S. Department of Transportation, March 2000.
13. Jacobsen, K., D. Tyrell, and A. B. Perlman. *Impact Test of a Crash-Energy Management Passenger Rail Car*. Paper No. RTD2004-66045, American Society of Mechanical Engineers, April 2004.
14. Tyrell, D., K. Severson, J. Zolock, and A. B. Perlman. *Passenger Rail Two-Car Impact Test, Volume I: Overview and Selected Results*. DOT/FRA/ORD-01/22.I. Federal Railroad Administration, U.S. Department of Transportation, January 2002.
15. Jacobsen, K., D. Tyrell, and A. B. Perlman. *Impact Tests of Crash Energy Management Passenger Rail Cars: Analysis and Structural Measurements*. Paper No. IMECE2004-61252, American Society of Mechanical Engineers, November 2004.
16. Tyrell, D. *Passenger Rail Train-to-Train Impact Test, Volume I: Overview and Selected Results*. DOT/FRA/ORD-03/17.I. Federal Railroad Administration, U.S. Department of Transportation, July 2003.
17. Tyrell, D., K. Jacobsen, and E. Martinez. *A Train-to-Train Impact Test of Crash Energy Management Passenger Rail Equipment: Structural Results*. Paper No. IMECE2006-13597, American Society of Mechanical Engineers, November 2006.
18. Parent, D., D. Tyrell, K. Jacobsen, and K. Severson. *Crashworthiness Analysis of the January 26, 2005, Glendale, California Rail Collision*. Paper No. JRC2011-56132, American Society of Mechanical Engineers, March 2011.
19. Tyrell, D., E. Martinez, K. Jacobsen, D. Parent, K. Severson, M. Priante, and A. B. Perlman. *Overview of a Crash Energy Management Specification for Passenger Rail Equipment*. Paper No. JRC2006-94044, American Society of Mechanical Engineers, April 2006.
20. Carolan, M., A. B. Perlman, and D. Tyrell. *Alternative Occupied Volume Integrity (OVI) Testing and Analyses*. Federal Railroad Administration, U.S. Department of Transportation, 2013 (in publication).