FTA Report No. 0233

FTA RESEARCH
FEDERAL TRANSIT ADMINISTRATION

Research Report and Findings: Crash Energy Management for Heavy Rail Vehicles, Light Rail Vehicles, and Streetcars

PREPARED BY

Enrico Sciandra and MaryClara Jones
Transportation Technology Center, Inc.
A subsidiary of the Association of American Railroads

OCTOBER
2022

U.S. Department of Transportation
Federal Transit Administration

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SPONSORED BY
Federal Transit Administration
Office of Research, Demonstration and Innovation
U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

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Abstract

This project was conducted as part of the Standards Development Program Cooperative Agreement with FTA's Research, Demonstration and Innovation and Transit Safety and Oversight offices. Project objectives included conducting background research and analysis on needs and gaps for new standards related to transit crashworthiness and crash energy management (CEM). Including a summary of transportation modes where standards are lacking, and on existing standards implemented into industry related to crashworthiness and CEM and industry survey results on the use of the standards for newly-procured equipment. The report includes findings related to development of standards, protocols, guidelines or recommended practices related to transit crashworthiness and CEM.

Executive Summary

The Federal Transit Administration (FTA) entered into a cooperative agreement with the Center for Urban Transportation Research (CUTR) at the University of South Florida to research areas of transit safety risk, identify existing standards and recommended practices to address those areas of risk, and perform a gap analysis to establish the need for additional standards, guidance, or recommended practices to support and further the safe operation of the nation's public transportation industry. At the direction of FTA, CUTR and its research partner, the Transportation Technology Center, Inc. (TTCI), are performing research and background studies on various topics to collect the information necessary for FTA to issue recommendations to the industry on voluntary standards or publish guidance documents or resource reports to assist the industry in mitigating areas of safety risk. The findings of this report, and subsequent guidance, can be leveraged to guide public transit agency decision-making. One area of research was crash worthiness and crash energy management (CEM) for rail transit rolling stock (heavy rail vehicles, light rail vehicles, and streetcars).

CEM is a performance-based technique that is used to improve passenger safety. Passenger injuries are the result of two main mechanisms—primary and secondary collisions. A primary collision produces high acceleration levels due to the impact of the train with another substantial structure (for example, another railcar). The possibility of an external object penetrating the railcar during a primary collision is high. Secondary impacts occur between the passengers and interior fittings or other passengers. Secondary impacts represent a major injury mechanism during low-speed crashes. CEM components are designed to reduce acceleration inside the car during the crash and avoid overriding derailments that cause structure penetration.

The need for CEM-equipped rail transit vehicles is highlighted by National Transportation Safety Board (NTSB) recommendations due to several accidents between 1996 and 2009. The recommendations were directed at either rail transit agencies specifically or FTA to implement crashworthiness equipment and standards. A research report about light rail vehicle (LRV) crashworthiness analyzes the injury mechanisms of passengers depending on seat layout in different energy level crash scenarios; the most common injuries are to the head, neck, and femur.[1]

The U.S. mandates crashworthiness for commuter passenger rail (Tier I and Tier II), whereas Europe mandates crashworthiness for all rail transport modes. The U.S. has two American Society of Mechanical Engineering (ASME) standards for addressing heavy rail and LRV crashworthiness. These ASME standards

[1] Olivares, G., 2011, *Crashworthiness Evaluation of Light Rail Vehicle Interiors*, Federal Transit Administration, FTA Report No. 0005.

have criteria for heavy rail and light rail, including streetcars, to assess the crashworthiness needs for structural strength and CEM. The American Public Transportation Association (APTA) developed standards for commuter rail structural crashworthiness, interior fittings, and seat performance. The APTA standard describes seat performance by means of passenger injury criteria, referring to the biomechanical limit fixed by the National Highway Traffic Safety Administration (NHTSA) in the Federal Motor Vehicle Safety Standards (FMVSS).

Several existing standards could directly address structural performance with or without modifications for light rail, streetcars, and heavy rail transit vehicles. Rail passenger performance standards do not address biomechanical limits. However, injury criteria, including biomechanical limits for evaluating passenger performance, are extensively used in the automotive industry. These criteria could be directly applied to the rail transit industry because the standards are structurally independent. Biomechanical limits are limits for survivability related to head acceleration, head injury, chest compression, and other factors.

An industry data collection effort was completed to investigate implementation of crashworthiness and CEM on transit railcars, including the standards used. The data collection effort used State Safety Oversight Agencies (SSOA) contacts to collect data from rail transit agencies in the representative states. Analysis of the data from the 31 rail transit agencies that responded shows that CEM-equipped rail transit vehicles represent almost 54% (5,840 railcars) of these agencies' existing fleets (10,781 railcars). Breaking down the data by transportation mode, CEM-equipped vehicles represent 59% of their heavy rail vehicles (5,173), 33% of their LRVs (644), and 22% of their streetcars (23).

Based on the research results and feedback from the CUTR Transit Safety Standards Working Group, several findings are indicated:

- Finding 1: ASME RT-1-2015 and ASME RT-2-2014 standards provide new procurement crashworthiness/CEM guidelines.
- Finding 2: There are interior vehicle designs for new and rehabilitation procurements, including passenger seating devices, attachments and tracking/anchorages, and seatback designs, that minimize passenger secondary impacts associated with collisions.
- Finding 3: There are risks associated with collisions of CEM-equipped revenue rail vehicles interacting with non-CEM-equipped rail vehicles, as identified by FTA research and real-world incidents.

Section 1 Introduction

The Federal Transit Administration (FTA) entered into a cooperative agreement with the Center for Urban Transportation Research (CUTR) at the University of South Florida to research areas of transit safety risk, identify existing standards and recommended practices to address those areas of risk, and perform a gap analysis to establish the need for additional standards, guidance, or recommended practices to support and further the safe operation of the nation's public transportation industry. At the direction of FTA, CUTR and its research partner, the Transportation Technology Center, Inc. (TTCI), are performing research and background studies on various topics to collect the information necessary for FTA to provide findings to the industry on voluntary standards or publish guidance documents or resource reports to assist the industry in mitigating areas of risk. The findings of this report and subsequent guidance can be leveraged to guide public transit agency decision-making. This report is on crashworthiness and crash energy management (CEM) for rail transit system rolling stock.

CEM is a crashworthiness strategy that incorporates crush zones into the design of passenger railcars. During a collision, crush zones are engineered to collapse in a controlled manner and distribute the crushed area to unoccupied areas throughout a train. This approach manages the dissipation of the collision energy more effectively and efficiently than conventional railcar designs.

During a train crash, passengers can be injured or killed due to two main mechanisms that arise because of sudden vehicle acceleration or deceleration or mechanical damage to the vehicle structure. The secondary impact of a passenger with interior fittings or other passengers is the principal injury mechanism for low-speed crashes, according to light rail vehicle (LRV) interior crashworthiness evaluation research. Injuries involve primarily the head, neck, and femur, and the gravity of each is described by related injury criteria developed by the National Highway Traffic Safety Administration (NHTSA) in the Federal Motor Vehicle Safety Standards (FMVSS).

CEM is currently required for Tier II commuter passenger railway vehicles. However, other U.S. standards and European regulations describe crashworthiness for other transportation rail modes, including rail transit. The automotive transportation industry has focused heavily on crashworthiness. Whereas vehicle size and structure are significantly different from railcars, some of the requirements prescribed for automobiles are reviewed in this research, specifically performance criteria, as they may be relevant to the rail industry.

[2] Jacobsen, K. M., 2008, "Collision Dynamics Modeling of Crash Energy Management Passenger Rail Equipment," Thesis, TUFTS University.
[3] Olivares, *op cit.*

Section 2 Industry Need

Researchers evaluated the need for CEM standards in rail transit by reviewing available reports published by the National Transportation Safety Board (NTSB) and other entities. The following summarizes the main findings of the NTSB reports regarding CEM:

- Investigation of a Washington Metropolitan Area Transit Authority (WMATA) Metrorail subway train crash in January 1996, which killed one person, led to the NTSB recommendation to WMATA to "undertake, with the assistance of qualified engineering support, a comprehensive evaluation of the design specifications of all series of Metrorail cars with respect to resisting carbody telescoping and providing better passenger protection, and make the necessary modifications, such as incorporating underframe bracing or similar features, to improve the crashworthiness for cars in the current and/or future Metrorail car."[4] WMATA found that modifications to the 1000-series railcars (Rohr-built) were impractical and embarked on procurement of the 7000-series railcars. The 5000-, 6000-, and 7000-series railcars have crashworthiness components designed for absorbing maximum energy in a collision and reducing accelerations to passengers.
- In 2004, a collision between two WMATA Metrorail trains occurred, injuring 20 people. NTSB recommended to WMATA to "either accelerate retirement of Rohr-built railcars, or if those railcars are not retired but instead rehabilitated, then the Rohr-built passenger railcars should incorporate a retrofit of crashworthiness collision protection that is comparable to the 6000-series railcars."[5] In addition, NTSB recommended to FTA to "develop minimum crashworthiness standards to prevent the telescoping of transit railcars in collisions and establish a timetable for removing equipment that cannot be modified to meet the new standards."[6]
- A 2008 accident with one fatality and seven injuries on the Green Line of Massachusetts Bay Transportation Authority (MBTA) was caused by loss of survival space in the train operator compartment. Although the two railcars involved were equipped with anti-climb devices, the understructure and end structure failed on both trolley cars, resulting in the loss of more than 10 ft of survivable space on both railcars. One of the resulting NTSB recommendations was exactly the same as the recommendation in 2004 for WMATA, to "develop minimum crashworthiness standards to prevent the telescoping of transit railcars in collisions and establish a timeline for removing the equipment that cannot be modified to meet the new standards." FTA responded that it would

[4] National Transportation Safety Board (NTSB), 1996, Safety Recommendation R-96-037.
[5] NTSB, 2006, Safety Recommendation R-06-002.
[6] NTSB, 2006, Safety Recommendation R-06-002.

work with the American Public Transportation Association (APTA) and the American Society of Mechanical Engineers (ASME) to develop rail transit vehicle CEM specifications. FTA also noted that it would research CEM specifications for overhauling the front ends of existing LRVs.[7]

- In 2009, a WMATA Metrorail train with 1000-series railcars struck a train with 3000-series and 5000-series railcars, killing 9 people including the train operator and 8 passengers and injuring another 80 people. The collision caused telescoping of the train that was hit. NTSB concluded that the "severity of the passenger injuries and number of fatalities was WMATA's failure to replace or retrofit the 1000-series railcars after those were shown in a previous accident to exhibit poor crashworthiness."[8]

The available safety data for heavy rail, light rail, and streetcar incidents in the National Transit Database (NTD) provide some insight into the types of events related to safety; although the detail supplied does not allow for a direct correlation to injuries or fatalities that could be prevented ,or minimized, by implementation of CEM in railcars. However, FTA's report detailing results from 2013 data offers insight into the magnitude of collisions in which CEM implementation in rail transit might help prevent injuries or fatalities. This report defines "collision" as a railcar colliding with another vehicle (rail or non-rail). In addition, the data are standardized by vehicle revenue miles.[9]

In heavy rail incidents, collisions are typically with another train, as train-to-automobile collisions are minimal due to limited interaction with automobiles. Injuries resulting from heavy rail train-to-train collisions increased by over 400% between 2011 and 2013, from approximately 1 injury every 100 million vehicle revenue miles in 2011 to approximately 5.5 injuries every 100 million vehicle revenue miles in 2013. Although train-to-train collisions are rare, they could have severe consequences in terms of available space for passenger survivability if telescoping between the railcars occurs and due to secondary impact injuries related to interior railcar fittings. Light rail or streetcar train-to-automobile collisions accounted for 71% of all light rail and streetcar collision injuries in 2013. Note that the data analyzed do not indicate if the injuries or fatalities were in the automobile or railcar.

Research published by FTA about light rail crashworthiness analyzed the different injuries that passengers can suffer depending on seating position. The research categorized LRVs in the U.S. according to internal and external characteristics. Internal characteristics refer to internal dimensions, weight,

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[7] NTSB, 2009, "Collision Between Two Massachusetts Bay Transportation Authority Green Line Trains Newton, Massachusetts, May 28, 2008," NTSB/RAR-09/02 PB2009-916302.

[8] NTSB, 2010, "Railroad Accident Report – Collision of Two Washington Metropolitan Area Transit Authority Metrorail Trains Near Fort Totten Station, Washington, DC, June 22, 2009," NTSB/RAR-10/02 PB2010-916302.

[9] Federal Transit Administration, 2013, "Rail Safety Statistics Report."

number of seats, type of seats, and layout, and external characteristics refer to whether the vehicle is low-floor or high-floor and CEM-equipped. Results from a survey indicated that 68% of the LRVs in the U.S. are high-floor vehicles and the remaining 32% are low-floor vehicles. The data collected also show that 66% of the high-floor LRVs and 38% of the low-floor LRVs are not equipped with CEM. Simulations were performed considering different seating layouts and different passenger sizes to evaluate LRV interiors' crashworthiness. According to the study, the most common injuries occurred in the head, neck, and femur due to the following:

- Forward-facing seats – contact with seatback structure
- Aft/rear-facing seats – low seatback structure does not support head
- Seats facing each other, lateral and perimeter seats – passenger body-to-body contact injuries

The research recommendation was to redesign seatback structures considering the height, seatback angle, padded surfaces, and other requirements, and the related injury criteria used for the analysis referred to FMVSS.[10] The results from the study correlate the injury criteria to the seating configurations.[11] The study also pointed out some recommendations for adopting simple restraint systems for child safety and anchor points for mobility devices.

Passenger Injury Mechanisms

Injuries and fatalities from a collision or sudden acceleration or deceleration events can be grouped into two passenger injury mechanisms:

- Primary collision of the vehicle with another vehicle or obstacle that results in two main outcomes—occupant-compartment crush and consequent reduction of survival space or penetration of the compartment by parts of the impacting vehicle (Figure 2-1).
- Secondary impacts between occupants and the vehicle interior (compartment interior surfaces, other occupants, loose objects) that occur after the primary collision (Figure 2-2).

[10] National Highway Traffic Safety Administration, 2004, 49 CFR Transportation, Chapter V Part 571, Federal Motor Vehicle Safety Standards; 49 CFR § 571.208; Occupant crash protection.
[11] Olivares, *op. cit.*

Figure 2-1 *Decrease in occupant survival space and intrusion of external object*[12]

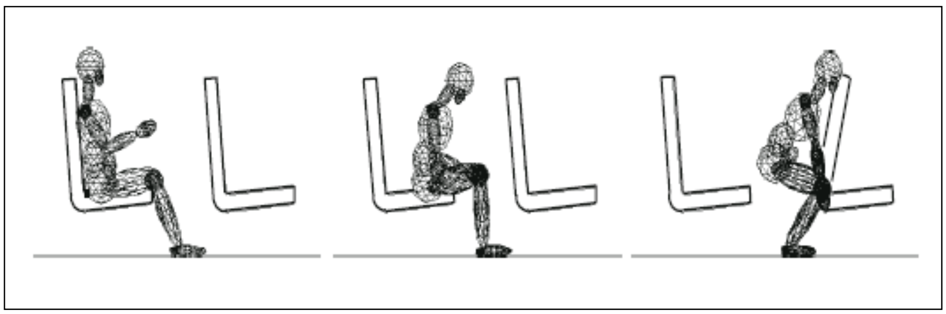

Figure 2-2 *Secondary impact*[13]

The primary advantages of a CEM design in reducing injuries and fatalities due to the primary collision and resulting secondary impacts is that the behavior of the vehicles involved is more predictable and the structure fails in a controlled manner. Although the energy imparted into the vehicle is merely a function of mass and speed, the CEM system dissipates this collision energy and reduces the peak acceleration to the vehicle and its passengers. Reducing the acceleration peak and creating a crush zone (i.e., zone in the car structure designed to crumple or collapse in a controlled manner) that prevents the opposing vehicles from climbing over each other or moving sideways relative to each other helps to keep the vehicles upright, in-line, and on the track. Keeping the impacted cars engaged (in-line with minimal vertical and lateral movement) also helps to direct the impact forces into the strongest parts of the respective car structures in a controlled manner. The probability of injury to crew and passengers is reduced because secondary impacts with seats, fixtures, and

[12] Carolan, M., K. Jacobsen, P. Llana, et al., 2011, "Technical Criteria and Procedures for Evaluating the Crashworthiness and Occupant Protection Performance of Alternatively Designed Passenger Rail Equipment for Use in Tier I Service," Federal Railroad Administration, DOT/FRA/ORD-11/22.
[13] Tyrell, D., K. Severson, and B. Marquis, 1998, "Crashworthiness of Passenger Trains," Federal Railroad Administration, DOT/FRA/ORD-97/10.

other interior components are minimized, as long as the passenger space is not compromised.[14]

Literature on Crashworthiness/CEM Research Related to Injuries and Fatalities

Research done by the Federal Railroad Administration (FRA) for commuter rail passenger cars showed that for train collisions above 70 mph, the CEM approach is significantly more effective than the conventional approach in preserving occupant volume (space in the railcar that passengers and crew normally occupy without being crushed). Although not all transit systems operate upward of 70 mph, the CEM design provides substantially gentler initial deceleration than the conventional design, even at slower speeds.[15] A "conventional approach" means the structure is designed through "conventional" load, such as corner post and compression load, without considering energy dissipation during the impact. The conventional approach stiffens the structure to prevent any deformation that can lead to loss of the passenger compartment. Figure 2-3 shows the CEM design that includes dissipation of impact energy through deformation of the vehicle's crushable elements/areas. The two strategies seem to contrast, but it is possible to have a stiff carbody along with deformable carbody structure and components at the car ends.

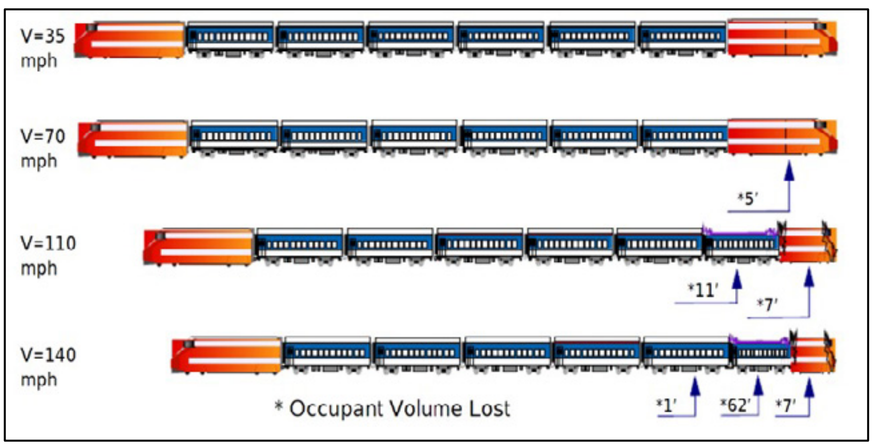

Figure 2-3 *Occupant volume loss for range of closing speeds, power car to power car collision, initially moving consist, CEM design*[16]

A comparison of CEM vs. conventional design on secondary impact velocity for a train-to-train collision at 100 mph is shown in Figure 2-4. Secondary impact

[14] Gough, G., G. Hud, and R. Carey, 2016, "A Workable Solution to Conflicting Crashworthiness Requirements." In 13th National Light Rail and Streetcar Conference: Transforming Urban Areas, Transportation Research Circular E-C213, Washington, DC: Transportation Research Board.
[15] Tyrell et al., op. cit.
[16] Tyrell, D. C., K. Severson, and B. P. Marquis, 1995, "Train Crashworthiness Design for Occupant Survivability," *Crashworthiness and Occupant Protection in Transportation Systems*, ASME, AMD Vol. 210/BED Vol. 30.

velocities are not strongly influenced by the primary collision speed because they are principally a function of the first portion of the deceleration pulse. The CEM design significantly lowers secondary impact velocities, which is expected to result in fewer fatalities and injuries due to secondary impacts of the occupants with the interior.

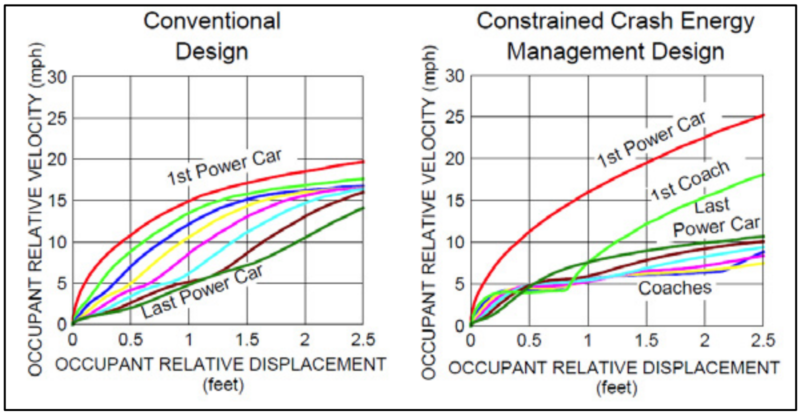

Figure 2-4 *Secondary impact velocity for conventional coach car design (left) vs. CEM design (right)*[17]

The Volpe National Transportation Systems Center published a report on injuries due to secondary impact on commuter and intercity passenger trains that analyzed 23 commuter and intercity passenger train accidents that occurred over 20 years and assessed the potential effectiveness of alternative strategies in injury mitigation. The strategies with the greatest potential to increase passenger safety are interior occupant protection (compartmentalization and padding), coupler integrity, CEM, end structure integrity, side structure integrity, and glazing system integrity. Not all recommendations are specifically applicable to rail transit vehicles,[18] but those that are applicable include the following:

- Compartmentalization was identified as an area that would save lives and reduce injuries and is a design strategy that ranked highest, aiming to decelerate passenger motion more gradually with the carbody rather than rapidly against the carbody by keeping individuals or groups of passengers in a smaller volume.
- CEM, end strength, and side strength had the second-highest ranking for reducing fatalities and injuries during a crash.
- Interior fixture attachment (loose equipment such as a loose seat attachment) poses a significant risk in a crash. A design change that secures attachments was recommended.

[17] *Ibid*.
[18] Wilson, B., and D. Tyrell, 2016, "Reducing the Harm in Rail Crashes: Analysis of Injury Mechanism and Mitigation Strategies," No. JRC2016-5811, in *Proceedings of the ASME IEEE ASCE 2016 Joint Rail Conference*.

Leading potential design changes include compartmentalization and seat design. Many non-fatal injuries occurred when passengers hit the hard seatbacks or tray tables in front of them. A modification to the seatbacks, such as incorporating more energy-absorbing materials, might prevent injuries. Luggage racks and tables also caused numerous non-fatal injuries. Table 2-1 tabulates design changes intended to address fatal injuries, non-fatal injuries, and risks.

Table 2-1 *Design Change for Fatal Injuries, Non-fatal Injuries, and Risks*

Design Change	Almost Certain	Probable	Possible	Total
Fatal Injuries				
Compartmentalization	5	1	0	6
Coupler separation	0	3	2	5
Crash energy management	5	0	0	5
End strength	5	0	0	5
Side strength	4	1	0	5
Windows	4	0	0	4
Seats	2	0	0	2
Third-rail end cap	1	0	0	1
Bulkheads	1	0	0	1
Catenary poles	0	1	0	1
Doors	1	0	0	1
Egress	0	1	0	1
End frame strength	1	0	0	1
Interior	0	1	0	1
Luggage rack	0	1	0	1
Panels and flooring	1	0	0	1
Passenger seats	0	1	0	1
Tables	1	0	0	1
Total	31	10	2	43
Non-fatal Injuries				
Compartmentalization	12	2	0	14
Seats	7	6	1	14
Luggage rack	4	2	0	6
Tables	4	1	0	5
Coupler separation	0	2	2	4
Bulkheads	2	1	0	3
Passenger seats	1	1	1	3
Anti-climber (override)	0	2	0	2
Windows	2	0	0	2
Crash energy management	0	1	0	1

Design Change	Almost Certain	Probable	Possible	Total
Fatal Injuries				
End strength	0	1	0	1
Floor strength	1	0	0	1
Panels and flooring	1	0	0	1
Panels/carbody end caps	0	1	0	1
Side strength	0	1	0	1
Truck attachment	0	1	0	1
Total	34	22	4	60
Risks				
Fixture retention	1	8	0	9
Seats	2	2	0	4
Training	0	3	0	3
Coupler separation	0	2	0	2
End frame strength	0	2	0	2
Floor strength	0	2	0	2
Fuel tank integrity	2	0	0	2
Interior	0	2	0	2
Record keeping	0	2	0	2
Side strength	1	1	0	2
Bridge abutments	0	1	0	1
Luggage rack	0	1	0	1
Passenger restraints	0	1	0	1
Roof strength	0	1	0	1
Tables	0	1	0	1
Windows	0	0	1	1
Total	6	29	1	36

Several research projects to address rail transportation safety were funded by the European Commission, with research objectives to issue guidelines for crashworthiness requirements for European standards. The European Rail Research Advisory Council (ERRAC) is an advisory body to the European Union (EU) representing member states, the railway manufacturing and supply industries, rail operators, infrastructure managers, users, academia, environmental and urban planning organizations, and the EU. Its primary mission is to establish and carry forward a strategic rail research agenda to meet safety targets for 2020 (Table 2-2) through research projects in five thematic areas. Only the safety-related projects are mentioned in this report.

Table 2-2 *Impact of ERRAC's Strategic Rail Research Agenda on European Rail Safety Scene*[19]

Safety Measurement	Present Situation (2000)	Impact of Present Measurements (2020)	Impact of ERRAC Measurements (2020)
Number of European Railway passenger fatalities per year	150	130 (-10%)	75 (-50%)
Total number of European Railway fatalities per year	900	500 (-30%)	200 (-75%)

SAFETRAIN and SAFETRAM[20] were research projects completed in 2001 on train crashworthiness for Europe. The main objective was to reduce the number of fatalities and serious injuries in railway accidents through new, improved designs of vehicle structure. SAFEINTERIORS was a European research project in 2010 that aimed to provide the scientific and technological basis to implement a consistent methodology to design, test, and validate improved interior solutions, thus reducing fatalities and injuries in rail accidents. This new interior passive safety framework provides a systematic approach to drastically reduce injuries and fatalities by combining the railway structural crashworthiness (closely linked with primary collision events) with injury biomechanics directly associated with secondary collisions. The injury mechanism is different for each crash scenario, so various kinds of injury criteria were developed.

SAFEINTERIORS developed a tool kit that includes a defined set of injury criteria with limits, test devices, and test methods to assess potential occupant injury levels in all foreseeable rail applications. Table 2-3 suggests the biomechanical values to consider for each body segment depending on the anthropomorphic test device (ATD), also known as a crash dummy, used for the testing and provides the information source for each injury criterion. Most injury criteria are obtained from automotive regulations developed by the United Nations Economic Council for Europe (UNECE), NHTSA, and other national organizations or best practices such as European New Car Assessment Protocol (Euro NCAP) and Insurance Institute of Highway Safety (IIHS).

[19] http://www.eurailsafe.net/errac.shtml.
[20] Data from SAFETRAIN and SAFETRAM were not available for this report but may allow further analysis of transit-specific collision performance. Further, studies completed by mass transit railcar manufacturers for modern procurements may assist in developing a transit-specific CEM body of knowledge.

Table 2-3 *Summary of Test Devices Available to Measure Recommended Injury Criteria*[21]

Test Devices – 50th %ile ADULT MALE ATDs

Body Region	Injury Criteria	Front impact: Hybrid III 50th%ile	Front impact: Hybrid III + Thor (Alex Lower Leg)	Front impact: FAA Hybrid III 50th%ile	Front impact: Rail Dummy (Hybrid III - RS)	Front impact: THOR	Rear impact: Hybrid III (TRID Neck)	Rear impact: RID2	Rear impact: BioRID II	Side impact: US SID / US DOT SID	Side impact: SID-HIII	Side impact: EuroSID (ES-1)	Side impact: ES-2	Side impact: ES-2re	Side impact: BioSID	Side impact: WorldSID
Head	HIC	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
	Res Accel 3ms	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Face	Facial Pressure															
	Facial Loads															
Neck	Axial Force	•	•	•	•	•	•	•	•		•	•	•	•	•	•
	Shear Force	•	•	•	•	•	•	•	•		•	•	•	•	•	•
	Bending Moment	•	•	•	•	•	•	•	•		•	•	•	•	•	•
	Nij	•	•	•	•	•	•									
Thorax	Localised Rib Deflection (Frontal)				•	•										
	Localised VC (Frontal)				•	•										
	Localised Rib Deflection (Lateral)											•	•	•	•	
	Localised VC (Lateral)							•				•	•	•	•	
Abdomen	Compression (Frontal)				•	•										
	VC (Frontal)				•	•										
	Compression (Lateral)														•	•
	VC (Lateral)														•	•
Upper Leg	Knee Displacement	•	•	•	•	•	•									
	Femur Axial Force	•	•	•	•	•	•						•	•		
Lower Leg	Tibia Axial Force	•	•	•	•		•									
	Tibia Index	•	•	•	•	•	•									
	Approval and accepted use	Code of Federal Regulation - 49, Part 572, Sub-Part E (FMVSS208) EEC 96/98/EC / ECE R94 ADR 69 & 73 GB11551-2003 USNCAP, EuroNCAP, AusNCAP, JAPNCAP			In development AV/ST9001 and GM/RT2100 Rail Specifications	In development		In development ??	EuroNCAP 2009 Whiplash assessment	Code of Federal Regulation - 49, Part 572, Sub-part F (FMVSS214)	Code of Federal Regulation - 49, Part 572, Sub-part M (FMVSS201)	EEC 96/27/EC	ECE R95 / EuroNCAP	USNCAP FMVSS214 (front seat occupant)	Not used in standards. Used for development only.	In development
	Transferable to Rail, Y/N?															
	MADYMO model available	•	•	•	○	•	•	•	•	•		•	•	•	•	•
	DYNA model available	•	•						•	•	•	•	•	•		•
	PAMCRASH model available	•								•		•	•	•		
	RADIOSS model available	•								•	•	•	•	•		
	ABAQUS model available												•			

Test Devices – 95th %ile ADULT MALE ATDs, 5th %ile ADULT FEMALE ATDs, CHILD ATDs, Pedestrian ATD

Body Region	Injury Criteria	95th %ile ADULT MALE ATDs – Front impact: Hybrid III 95th%ile	5th %ile ADULT FEMALE ATDs – Front impact: Hybrid III 5th%ile	5th %ile ADULT FEMALE ATDs – Side impact: SID-IIs	5th %ile ADULT FEMALE ATDs – Side impact: SID-IIs FRG	5th %ile ADULT FEMALE ATDs – Side impact: WorldSID 5th%ile	CHILD ATDs – Front impact: Hybrid III 6YO	CHILD ATDs – Front impact: TNO P6	CHILD ATDs – Multi-directional: TNO Q6	Pedestrian ATD – Multi-directional: Polar II
Head	HIC	•	•	•	•	•	•	•		
	Res Accel 3ms	•	•	•	•	•	•	•		
Face	Facial Pressure									
	Facial Loads									
Neck	Axial Force	•	•	•	•	•	•			
	Shear Force	•	•	•	•	•	•			
	Bending Moment	•	•	•	•	•	•			
	Nij	•	•							
Thorax	Localised Rib Deflection (Frontal)									
	Localised VC (Frontal)									
	Localised Rib Deflection (Lateral)			•	•					
	Localised VC (Lateral)			•	•					
Abdomen	Compression (Frontal)									
	VC (Frontal)									
	Compression (Lateral)			•	•	•				
	VC (Lateral)			•	•	•				
Upper Leg	Knee Displacement	•	•							
	Femur Axial Force	•	•				•			
Lower Leg	Tibia Axial Force	•	•							
	Tibia Index	•	•							
	Approval and accepted use	Code of Federal Regulation - 49, Part 572, Sub-Part	Code of Federal Regulation - 49, Part 572, Sub-Part O (FMVSS208) USNCAP	USNCAP (rear occupant) IIHS FMVSS214		In development	Code of Federal Regulation - 49, Part 572 Sub-Part N, (FMVSS208 OOP)	ECE R44		Developed in a joint collaboration of GESAC, Honda R&D, and JARI
	Transferable to Rail, Y/N?									
	MADYMO model available	•	•	•			•	•		
	DYNA model available	•	•	•		•	•			
	PAMCRASH model available	•	•	•		•	•			
	RADIOSS model available	•	•	•			•	•		
	ABAQUS model available			•						

Test Devices – Components

Body Region	Injury Criteria	Headforms: (SAE821) Rigid Headform (6.8kg)	Headforms: (SAE) Flat Impactor with Honeycomb Disc (6.8kg)	Headforms: (NHTSA) Free Motion Headform	Headforms: Pedestrian Adult Headform (4.6kg)	Headforms: Pedestrian Child Headform (2.5kg)	Headforms: Pedestrian Child/small adult Headform (3.5kg)	Headforms: Pedestrian Adult Headform (4.5kg)	Legforms: Pedestrian Upper Leg	Legforms: Pedestrian Lower Legform	Legforms: FlexPLI legform
Head	HIC	•	•	•	•	•	•	•			
	Res Accel 3ms	•	•	•	•	•	•	•			
Face	Facial Pressure										
	Facial Loads										
Neck	Axial Force										
	Shear Force										
	Bending Moment										
	Nij										
Thorax	Localised Rib Deflection (Frontal)										
	Localised VC (Frontal)										
	Localised Rib Deflection (Lateral)										
	Localised VC (Lateral)										
Abdomen	Compression (Frontal)										
	VC (Frontal)										
	Compression (Lateral)										
	VC (Lateral)										
Upper Leg	Knee Displacement										
	Femur Axial Force										
Lower Leg	Tibia Axial Force										
	Tibia Index										
	Approval and accepted use	Code of Federal Regulation - 49, Part 572 Sub-Part L (FMVSS201) ECE R21, EEC 74/60/EC, ECE R12	ECE R12 EuroNCAP (steering wheels without airbags)	Code of Federal Regulation - 49, Part 572 Sub-Part L (FMVSS201) EU 2003/102/EC (phase 2)	Code of Federal Regulation - 49, Part 572, Sub-Part L EU 2003/102/EC (phase 2) EEVC WG17	Code of Federal Regulation - 49, Part 572, Sub-Part L EEVC WG17	EU 2003/102/EC (phase 1)	latest EU draft ped pro regulations (phase 2)	EU 2003/102/EC EuroNCAP	EU 2003/102/EC EuroNCAP	Developed by JAMA, JARI. Status: in development
	Transferable to Rail, Y/N?										
	MADYMO model available			•	•	•	•		•	•	
	DYNA model available			•	•	•	•		•	•	
	PAMCRASH model available			•							
	RADIOSS model available			•	•	•	•	•	•	•	
	ABAQUS model available										

[21] SAFEINTERIORS, 2010, "Publishable Final Activity Report," p. 6; Train Interior Passive Safety for Europe, Contract No. FP6-031260.

Working Group Discussion

The CUTR Transit Safety Standards Working Group was formed to provide guidance and industry stakeholder insight into the safety standards development process. Several meetings were held and many topics were discussed regarding the development of standards, implementation of standards, what the industry is using, and a number of topics not specifically referred to in NTSB reports or other research reports were discussed at length and are important to document. These topics included the following:

- Crashworthiness standards, such as those published by ASME or the European Committee for Standardization (EN standards), have only started to be implemented due to the recent publication of the standards, extended useful life of transit railcars, and length of time it takes to procure new rail transit vehicles. Stakeholders were aware of only a few agencies procuring new fleets according to ASME or EN standards, including Honolulu, WMATA, and MBTA.
- One agency procuring new fleets equipped with CEM indicated that the ASME standard for corner posts required a redesign related to the operator line-of-sight for operation.
- A member of the Transit Safety Standards Working Group whose transit agency is procuring new fleets equipped with CEM noted that the agency's specifications called for modular CEM components that can be replaced if damaged or if newer or better technology becomes available.
- Agencies with only some of their fleet equipped with CEM components should evaluate the interoperability of CEM-equipped vehicles with non–CEM-equipped vehicles and the effects mismatched equipment could have in a crash.

Section 3

Standards and Regulations

Several crashworthiness standards have been developed that aim to minimize injuries and fatalities. As shown in Table 3-1, the standards can be grouped into two categories:

- *Design-for-strength* standards include static load cases intended to result in specific design features that are presumed to be effective in the range of expected accident conditions. Design standards often implicitly assume specific design features, such as buff stops. Compliance with design standards can be verified by relatively simple closed-form calculations or nondestructive tests.
- *Performance-based* standards include impact scenarios intended to cover the range of potential accidents and attempt to prescribe desired performance under conditions closely related to those expected in a collision. Performance standards permit a wide range of design approaches.[22] The main advantage of performance requirements is that they require fewer assumptions on the design or details of the equipment, and the required performance is more closely related to the desired performance under collision conditions. Compliance typically requires detailed numerical simulation, destructive tests, or some combination of both.[23]

Table 3-1 *Safety Requirement Categorization*

	Design for Strength	Performance-Based	
Standard	Design-based	Structural performance-based	Passenger performance-based
Requirements	Static load the structure must withstand	Energy absorption (load vs. displacement)	Biomechanical limit values

Although design standards address the structural strength of the component/structure, the increased stiffness due to strength can also cause a lack of cushioning during impact. The result included higher peak accelerations after collision within the impacted railcars. Performance-based standards aim to address both structural and passenger performance by using a “design-for-safety” methodology. The automotive industry was at the forefront of adopting the design-for-safety paradigm over design-for-strength, and a similar safety-performance-over-strength analogy is being extended to the rail industry in Europe. The release of the 2010 amendments to safety design standard EN

[22] Tyrell, D. C., and P. Llana, 2015, “Locomotive Crashworthiness Research,” *Proceedings of the 2015 Stephenson Conference, Institute of Mechanical Engineers, April 21-23, 2015*, Volpe National Transportation System Center.

[23] Tyrell, D. C., 2002, “U.S. Rail Equipment Crashworthiness Standards,” *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* 216 (2): 123–30.

15227, Railway applications – Crashworthiness requirements for rail vehicles, was aimed at performance-based standards.[24] Several years later, ASME issued a comparable safety standard, ASME RT-1-2015: Safety Standard for Structural Requirements for Light Rail Vehicles.[25]

Performance-based standards can be both structural and passenger-based (Table 3-1):

- Structural performance-based standards can be defined as energy absorption (load vs. displacement).
- Passenger performance-based standards typically use criteria (biomechanical limit values) based on crash test ATDs (dummies that simulate the dimensions, weight proportions, and articulation of the human body). The population variability is represented by different ATD percentiles. The 50th percentile ATD male is equal in height and weight to the average North American male at the time of its development. The 5th percentile represents the totality of the value (height, weight, and dimension) below which 5% of the population may be found. The 95th percentile represents the totality of the value (height, weight, and dimension) below which 95% of the population may be found. ATDs representing children of different ages have been developed as well. Biomechanical limit values are defined for each percentile dummy. ATDs of varied percentiles represent different classes of people (e.g., adult male, adult female, three-year-old child).

Crash Energy Management

The purpose of design standards is to describe the minimum stiffness of a car to avoid survival space crushing and external object(s) intruding during a crash event. However, a stiff structure can lead to higher accelerations and decelerations inside the car during a crash event. Performance criteria must be specified to limit the passenger injury risk in the internal survival space.

CEM specifications can be categorized as structural performance regulations. The primary advantage of a CEM design is that the behavior of the vehicles involved in a crash is more predictable, and the structure fails in a controlled manner. Although the energy imparted into the vehicle is merely a function of mass and speed, the CEM system dissipates this collision energy, reducing the peak acceleration to which the vehicle and its passengers are exposed. Reducing this acceleration peak and creating a crush or crumple zone that is more likely to keep the two opposing vehicles engaged with each other, as shown in Figure 3-1, helps keep the vehicle upright, in-line, and on the track. This reduces the probability of injury to crew and passengers because

[24] EN 15227:2008 - Amendment 1:2010., adopted on January 1, 2011; pending 2016 amendment.
[25] Gough, Hud, and Carey, *op cit*.

secondary impacts with seats, fixtures, and other interior components are minimized, as long as the passenger space is not compromised. Reduction in damage to the surrounding infrastructure is also minimized, as the vehicles are less likely to leave the right-of-way.[26] For train collisions above 70 mph, the CEM approach is significantly more effective than the conventional approach in preserving occupant volume. The CEM design provides a significantly gentler initial deceleration of the impacted vehicles after collision for the full range of collision speeds than the conventional design.[27] Figure 3-1 clearly shows the differences between conventional (upper pictures) and CEM-equipped (lower pictures) vehicle crash performance.

Figure 3-1 *Conventional (top) and CEM-equipped (bottom) train-to-train crash tests*[28]

U.S. Railway Regulations

FRA regulations in the U.S. for passenger commuter rail transportation—Code of Federal Regulations (CFR) series 238 for Tier I and II, CFR series 229 for locomotive crashworthiness—can be categorized by the definition of design-based ("D") and performance-based (both structural, "SP," and passenger, "PP"). The federal regulations for commuter passenger vehicles are shown in Table 3-2. Tier I regulations apply to trains that operate at speeds up to 125 mph, and Tier II regulations apply to trains that operate 125–150 mph. Locomotives for all tiers have specific regulations, as shown in Table 3-2 as well.

[26] *Ibid*.
[27] Tyrell, Severson, and Marquis, *op. cit*.
[28] Carolan, Jacobsen, and Llana, *op cit*.

Table 3-2 *Federal Regulations for Commuter Passenger Vehicles*

Regulation #	Title	Applicability	Type
49 CFR § 238.203	Static end strength	Tier I	D
49 CFR § 238.205	Anti-climbing mechanism	Tier I	D
49 CFR § 238.207	Link between coupling mechanism and carbody	Tier I	D
49 CFR § 238.209	Forward end structure of locomotives, including cab cars and MU locomotives	Tier I	D
49 CFR § 238.211	Collision post	Tier I	D
49 CFR § 238.213	Corner post	Tier I	D
49 CFR § 238.215	Rollover strength	Tier I	D
49 CFR § 238.217	Side structure	Tier I	D
49 CFR § 238.219	Truck to carbody attachment	Tier I	D
49 CFR § 238.221	Glazing	Tier I	D
49 CFR § 238.223	Locomotive fuel tanks	Tier I	D
49 CFR § 238.233	Interior fittings and surfaces	Tier I	D
49 CFR § 238.405	Longitudinal static compression load	Tier II	D
49 CFR § 238.407	Anti-climbing mechanism	Tier II	D
49 CFR § 238.409	Forward end structure of power cabs	Tier II	D
49 CFR § 238.411	Rear end structure of power cabs	Tier II	D
49 CFR § 238.413	End structure of trailer cars	Tier II	D
49 CFR § 238.415	Rollover strength	Tier II	D
49 CFR § 238.417	Side loads	Tier II	D
49 CFR § 238.419	Truck to carbody attachment	Tier II	D
49 CFR § 238.421	Glazing	Tier II	D
49 CFR § 238.423	Fuel tanks	Tier II	D
49 CFR § 238.435	Interior fittings and surfaces	Tier II	D
49 CFR § 238.403	CEM	Tier II	SP/PP
49 CFR § 229, Appendix E	Performance criteria for locomotive crashworthiness	Locomotive	SP

D = design-based; MU = multiple unit; SP = structural performance–based; PP = passenger performance–based

California Railway Standards

The Public Utilities Commission of the State of California issued a document in 1991 concerning safety rules and regulations covering light rail transit and last revised it in January 2000.[29] The document specifies the general design and safety rules for a LRV in terms of lighting, brakes, equipment, traction, fire protection, and others. The section dealing with the structure specifies the strength of major structural components and the crashworthy structures of

[29] Public Utilities Commission of the State of California, "Safety Rules and Regulations Covering Light-Rail Transit," General Order 143-B, January 2000.

anti-climbing mechanisms, corner and collision posts, and windshields and windows. However, there are no requirements about energy absorption in case of an impact and no crashworthiness requirement for vehicle interiors.

Railway Standards

Standards developed in the U.S. are listed in Table 3-3. The AAR S-580 standard is a locomotive crashworthiness standard that is also referenced in the Code of Federal Regulations. ASME developed standards for LRVs, heavy rail vehicles, and streetcars; each standard addresses structural stiffness and CEM. Also listed, are recommended practices APTA has published as related to interior fittings, seating design, and design and construction of commuter railcars.

Table 3-3 *U.S. Railway Standards for Railway Vehicles*

Standard #	Title	Applicability
ASME RT-1-2015	Safety Standard for Structural Requirement for Light Rail Vehicles	Light Rail & Streetcars
ASME RT-2-2014	Safety Standard for Structural Requirement for Heavy Rail Vehicles	Heavy Rail
APTA PR-CS-S-006-98 Rev 2 [2006]	Standard for Attachment Strength of Interior Fittings for Passenger Railroad Equipment	Commuter Rail
APTA PR-CS-S-011-99	Standard for Cab Crew Seating Design	Cab Car of Commuter Rail
APTA PR-CS-S-016-99	Standard for Passenger Seats in Passenger Railcars	Commuter Rail
APTA PR-CS-S-034-99	Standard for the Design and Construction of Passenger Railroad Rolling Stock	Commuter Rail
AAR S-580	Locomotive Crashworthiness Requirements	Locomotive

ASME standards are design-based standards; Table 3-4 lists the standard, the rail mode for which the specification was written, and the structural member load cases. It is noteworthy that the load magnitude and its application direction as referred to under “Load Cases” differ between streetcars, LRVs, or heavy rail vehicles and are detailed in the standards.

Table 3-4 *ASME Standards – Structural Loads*

Standard #	Category	Load Cases
ASME RT-1-2015	LRVs, including streetcars	a) maximum vertical load b) end sill compression c) coupler anchorage loads d) coupling impact e) collision post load f) corner post loads g) structural shelf h) side wall load i) roof load j) truck to carbody attachment k) equipment attachment
ASME RT-2-2014	Heavy rail vehicles	

The ASME standards crashworthiness criteria for each vehicle type are summarized in Table 3-5. The acceptability criteria are based on vehicle structural performance.

Table 3-5 *ASME Standards – Crashworthiness*

Standard #	Category	Scenarios
ASME RT-1-2015	Streetcars	1) Low severity impact scenario: two identical streetcars, closing speed 8 km/h (5 mph) 2) Moderate severity impact scenario: two identical streetcars, closing speed 24 km/h (15 mph)
ASME RT-1-2015	LRVs	1) Low severity impact scenario: two identical LRVs, closing speed 8 km/h (5 mph) 2) Moderate severity impact scenario: two identical LRVs, closing speed 24 km/h (15 mph) 3) Severe impact scenario: two identical LRVs, closing speed 40 km/h (25 mph) 4) Collision with street vehicle: a) 150 kN longitudinal at vehicle centerline b) 100 kN corner load
ASME RT-2-2014	Heavy rail vehicles	1) Train-to-train impact @ 24 km/h (15 mph) 2) Train-to-train impact @ 40 km/h (25 mph)

APTA PR-CS-S-034-99 is a crashworthiness standard that specifies static and dynamic CEM requirements for commuter rail passenger rolling stock. Other standards have been developed by APTA related to the crashworthiness of interior fittings and seats for crew and passengers of commuter rail (Table 3-6). The passenger seats dynamic assessment (APTA PR-CS-S-016-99) requires dynamic testing with instrumented ATDs to measure biomechanical values during a simulated crash test. Head, neck, chest, and femur force and/or accelerations are measured. The related injury criteria are compared to the limit values defined in CFR 49 Part 571, Standard No. 208: Occupant Crash Protection.[30] The test configurations consider forward and backward facing seats, and acceptability criteria are established according to the injury criteria.

[30] National Highway Traffic Safety Administration, 2004, 49 CFR Transportation, Chapter V Part 571. Federal Motor Vehicle Safety Standards, 49 CFR § 571.208; Occupant crash protection.

Table 3-6 *APTA Standards*

Regulation #	Category	Load Cases
APTA PR-CS-S-006-98 Rev 2 [2006]	Interior fittings	Static load for: 1) luggage rack 2) handholds 3) windscreens and partitioning 4) miscellaneous interior fittings
APTA PR-CS-S-011-99	Seats for crew	Static load for: 1) bottom cushion 2) backrest 3) armrest 4) anti-rotation test Dynamic test for: 1) seat attachment
APTA PR-CS-S-016-99	Seats for passengers	Static load for: 1) backrest 2) grab handle 3) vertical seat strength 4) armrest 5) footrest 6) leg rest 7) tray table Dynamic test for: 1) forward facing seat attachment and human injury test 2) rearward facing seat attachment and human injury test 3) additional dynamic testing Seat durability testing: 1) mechanism 2) cushion and upholstery
APTA PR-CS-S-034-99	Passenger railroad rolling stock	Static load for: 1) static end compression strength 2) transverse strength requirements 3) end frame 4) roof 5) climb, bypass, and overturn resistance 6) truck to carbody attachment 7) equipment attachment 8) structural connections Dynamic test for: 1) crash energy management

U.S. vs. European Railway Regulations

Two European regulations address railway crashworthiness:

- EN 12663 (03/2010), Structural requirements of railway vehicle bodies, is categorized as a crashworthiness specification and is a design-for-strength regulation, as the requirements are design-based.
- EN 15227 (12/2010), Crashworthiness requirements for railway vehicle bodies, is categorized as a crashworthiness and CEM specification. It is a design-for-safety regulation with performance-based requirements.[31]

[31] Gough, Hud, and Carey, *op cit*.

European regulations set the rules for all European transportation modes, from locomotives to streetcars (Table 3-7). Each regulation categorizes vehicles in different ways based on the operational mode. EN 12663, "Railway applications – Structural requirements of railway vehicle bodies," is composed of two parts, one for passenger rolling stock and the second for freight cars.[32] For this report, freight car structural requirements were not analyzed. Among passenger railcars, the regulation categorizes five different kinds of vehicles. The loads that the cars must withstand are divided into longitudinal and vertical loads.

EN 15227, "Railway applications – Crashworthiness requirements for rail vehicles," applies to locomotive and passenger rolling stock.[33] The crashworthiness requirements are classified into four categories depending on operational mode. For each impacted vehicle category, four crash scenarios define the impact velocity and the impacted obstacles. This is a performance-based regulation, as the targets are related to vehicle structural performance.

Table 3-7 *Current European Regulations*

Regulation #	Applicability	Load Cases / Scenarios
EN 12663, Structural requirements of railway vehicle bodies	L: locomotive P-I: e.g., coaches P-II: e.g., fixed unit parts and coaches P-III: e.g., underground, rapid transit vehicles, and light railcar P-IV: e.g., light-duty metro and heavy-duty tramway vehicles P-V: e.g., tramway vehicles	1) Longitudinal static load for the vehicle body 2) Vertical static loads for the vehicle body 3) Static proof load at interfaces 4) General fatigue load cases for the vehicle body 5) Fatigue loads at interfaces 6) Modes of vibrations
EN 15227, Crashworthiness requirements for railway vehicle bodies	C-I: Vehicles designed to operate on TEN routes, international, national, and regional networks (which have level crossing) (e.g., locomotives, coaches, and fixed train units) C-II: Urban vehicles designed to operate only on a dedicated railway infrastructure, with no interface with road traffic (e.g., metro vehicles) C-III: LRVs designed to operate on urban and/or regional networks, in track sharing operation, and interfacing with road traffic (e.g., tram trains, per urban tram) C-IV: LRVs designed to operate on dedicated urban networks interfacing with road traffic (e.g., tramway vehicles)	1) Collision between identical train unit C-I: @ 36 km/h (22.4 mph) C-II: @ 25 km/h (15.5 mph) C-III: @ 25 km/h (15.5 mph) C-IV: @ 15 km/h (9.3 mph) 2) a) Collision with 80 t wagon C-I: @ 36 km/h (22.4 mph) C-III: @ 25 km/h (15.5 mph) b) Collision with 129 t regional train C-III: @ 10 km/h (6.2 mph) 3) c) Collision with 15 t deformable obstacle c-i) C-I: @ maximum train operational speed at a level crossing -50 km/h c-ii) @ ≤ 110 km/h (68.3 mph) C-III: @ 25 km/h (15.5 mph) d) collision with 3 t rigid obstacle C-IV: @ 25km/h (15.5 mph) 4) Collision with small low obstacle C-I and C-III, table defining the load per maximum operational speed

[32] Railway applications – Structural requirements of railway vehicle bodies, BS EN 12663-1:2010+A1:2014.
[33] Railway applications – Crashworthiness requirements for rail vehicles, BS EN 15227:2008+A1:2010.

Correspondence between European regulations and CFR regulations is presented in Table 3-8. Literature from Asia and Australia regarding crashworthiness and CEM also were reviewed, but the language was not included because they directly referenced U.S. and European standards already included in this literature summary.

Table 3-8 *Locomotive CFR vs. EU Performance-Based Regulations*

U.S. Regulation for Tier I	Type	EU Regulation	Type
§ 238.203 – Static end strength § 238.205 – Anti-climbing mechanism § 238.207 – Link between coupling mechanism and carbody § 238.209 – Forward end structure of locomotives, including cab cars and MU locomotives § 238.211 – Collision posts § 238.213 – Corner posts § 238.215 – Rollover strength § 238.217 – Side structure § 238.219 – Truck to carbody attachment § 238.221 – Glazing § 238.233 – Interior fittings and surfaces	D	EN 12663 – Structural requirements of railway vehicle bodies	D
U.S. Regulation for Tier II	**Type**	**EU Regulation**	**Type**
§ 238.403 – Crash energy management	SP/PP	EN 15227 – Crashworthiness requirements for railway vehicle bodies	SP
§ 238.405 – Longitudinal static compressive strength § 238.407 – Anti-climbing mechanism § 238.409 – Forward end structure of power car cabs § 238.411 – Rear end structure of power car cabs § 238.413 – End structure of trailer cars § 238.415 – Rollover strength § 238.417 – Side loads § 238.419 – Truck to carbody attachment § 238.421 – Glazing § 238.435 – Interior fittings and surfaces	D	EN 12663 – Structural requirements of railway vehicle bodies	D
U.S. Regulation for Locomotive	**Type**	**EU Regulation**	**Type**
§ 229 Appendix E – Locomotive crashworthiness design requirement	SP	EN 15227 – Crashworthiness requirements for railway vehicle bodies	SP

D = design-based; MU = multiple unit; SP = structural performance–based; PP = passenger performance–based

U.S. Rail Regulations vs. Automotive Standards

As the development and application of design for safety began in the automotive industry, it is worth comparing railway and automotive regulations as well as safety standards. New Car Assessment Protocol (NCAP) and Insurance Institute of Highway Safety (IIHS) standards are considered best practices among the automotive industry for Europe and the U.S., respectively. United Nations Economic Council for Europe (UNECE) regulations are equivalent to CFR U.S. railway standards about rollover (Table 3-9), side structure (Table 3-10), interior fittings (Table 3-11), and CEM (Table 3-12), which have been compared to Federal Motor Vehicle Safety Standards (FMVSS) automotive regulations and standards.

Table 3-9 *Railway vs. Automotive Rollover Regulations*

Railroad Regulation	Category	Automotive	Title	Type
49 CFR § 238.215 49 CFR § 238.415	Rollover for Tier I Rollover for Tier II	FMVSS 216a	Roof crush resistance	SP
		FMVSS 220	School bus rollover prevention	D
		UNECE R66	Rollover	SP
		UNECE R29	Cab of commercial vehicle	SP
		SAE J2422	Cab of commercial vehicle	SP
		IIHS	Roof strength	SP

D = design-based; SP = structural performance–based; PP = passenger performance–based; SAE = Society of Automotive Engineers

Table 3-10 *Railway vs. Automotive Side Structure Regulations*

Railroad Regulation	Category	Automotive	Title	Type
49 CFR § 238.217 49 CFR § 238.417	Side structure Tier I Side loads Tier II	FMVSS 214	Side impact protection	SP / PP
		FMVSS 226	Ejection mitigation	SP
		UNECE R95	Side impact protection	SP / PP
		UNECE R135	Pole side impact performance	SP / PP
		IIHS	Side test	SP / PP
		Euro NCAP	Side impact test protocol	SP / PP
		Euro NCAP	Oblique pole test protocol	SP / PP

SP = structural performance–based; PP = passenger performance–based

Table 3-11 *Railway vs. Automotive Interior Fittings Regulations*

Railroad Regulation	Category	Automotive	Title	Type
49 CFR § 238.233 49 CFR § 238.435	Interior fittings and surfaces Tier I Interior fittings and surfaces Tier II	FMVSS 201	Occupant protection in interior impact	PP
		FMVSS 207	Seats	D
		FMVSS 222	School bus passenger seating and crash protection	SP
		UNECE R21	Interior fittings	PP
		UNECE R25	Head restraints	PP
		UNECE R80	Seats and their anchorages (buses)	SP
		UNECE R137	Frontal crash, seat belt focus	PP
		Euro NCAP	Knee mapping	PP
		Euro NCAP	Whiplash	PP
		IIHS	Seat/head restraint evaluation protocol	PP

D = design-based; SP = structural performance–based; PP = passenger performance–based

Table 3-12 *Railway vs. Automotive CEM Regulations*

Railroad Regulation	Category	Automotive	Title	Type
49 CFR § 238.403	Crash energy management	FMVSS 208 UNECE R94	Occupant crash protection Occupant crash protection in frontal collision	PP SP / PP
		IIHS	Moderate overlap	SP / PP
		IIHS	Small overlap	SP / PP
		Euro NCAP	Frontal Offset-Deformable Barrier crash	SP / PP
		Euro NCAP	Frontal Full Width Rigid Barrier crash	SP / PP

SP = structural performance–based; PP = passenger performance–based

Other Safety-Related Road/Automotive Standards

There are other safety-related highway-feature standards, such as guardrails that work as CEM for road safety. Table 3-13 lists the two standards that recommend evaluating passenger performance in terms of biomechanical limit values.

Table 3-13 *Road Safety Standard*

Standard	Title	Type
MASH	Manual for Assessing Safety Hardware	SP / PP
NCHRP 350	Recommended Procedures for Safety Performance Evaluation of Highway Features	SP / PP

SP = structural performance–based; PP = passenger performance–based

Summary of Structural Standards and Regulations

The standards identified as structural standards were reviewed for specific types of requirements and their applicability to rail transit vehicles. Figure 3-2 and Figure 3-3 show examples of schematic load applications for corner and collision posts and compression load. Table 3-14 summarizes each regulation or standard's requirements, the mode for which the standard or regulation was specifically written, and the targeted type of structural requirement.

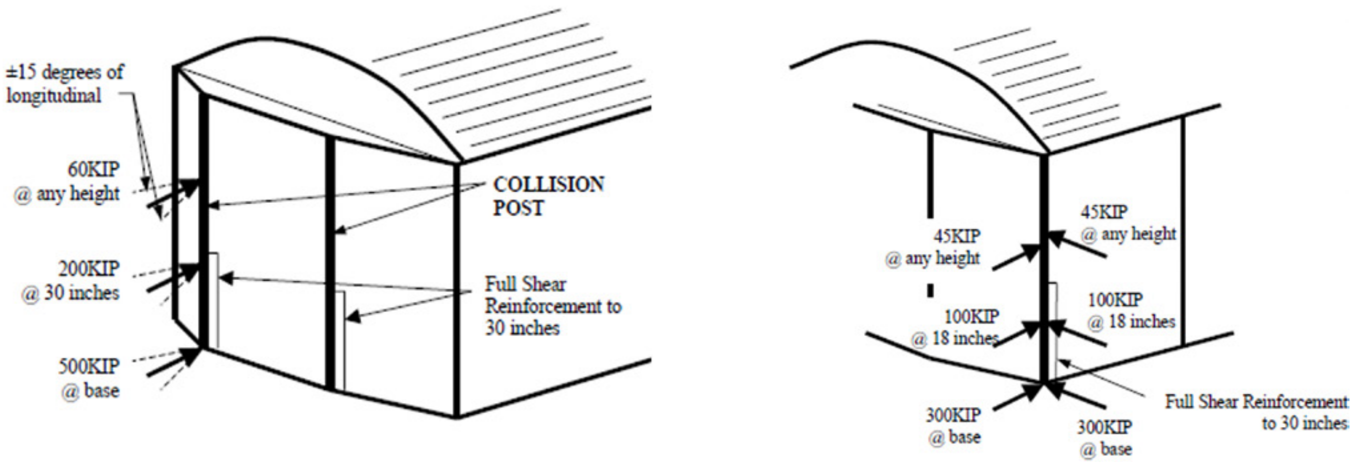

Figure 3-2 *Schematic of collision (left) and corner (right) post loads for MU and cab car (cab end only)*[34]

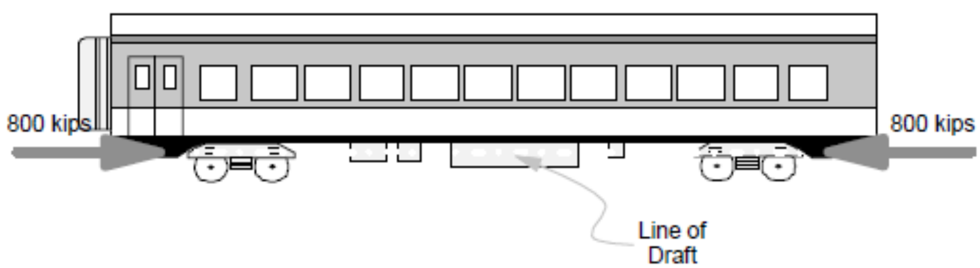

Figure 3-3 *Schematic of compression load on passenger car*[35]

[34] American Public Transportation Association, 2006, Standard for the Design and Construction of Passenger Railroad Rolling Stock., APTA PR-CS-S-034-99.
[35] Tyrell, D., and B. Perlman, 2003, "Evaluation of Rail Passenger Equipment Crashworthiness Strategies," *Transportation Research Record*, 1825 (1): 8–14.

Table 3-14 *Structural Topics Addressed by Each Standard*

	49 CFR § 238	49 CFR § 238	EN 12663	EN 15227	ASME RT-1-2015	ASME RT-2-2014	APTA PR-CS-S-006-98 Rev 2 [2006]	APTA PR-CS-S-011-99	APTA PR-CS-S-016-99	APTA PR-CS-S-034-99	49 CFR 229 Locomotive
	Commuter Rail Tier I	*Commuter Rail Tier II*	*All Transportation Modes*	*All Transportation Modes*	*Light Rail, Streetcars*	*Heavy Rail*	*Commuter Rail*	*Commuter Rail (Cab Crew Seats)*	*Commuter Rail (Passenger Seats)*	*Commuter Rail*	*Locomotive*
Crash Energy Management		X		X	X	X				X	
Static end strength/Longitudinal static compressive strength	X	X	X		X	X				X	
Anti-climbing mechanism	X	X		X	X	X				X	
Link between coupling mechanism and carbody	X				X	X					
Forward end structure of locomotives, including cab cars and MU locomotives/ Power car cabs	X	X								X	
Collision post	X				X	X				X	
Corner post	X				X	X				X	
Rollover strength	X	X			X	X				X	
Side structure/Side loads	X	X			X	X				X	
Truck to carbody attachment	X	X	X		X	X				X	
Glazing	X	X									
Fuel tanks	X	X									
Interior fittings and surfaces/equipment attachment	X	X	X		X	X	X	X	X	X	
Rearward end structure of power car cabs		X									
End structure of trailer cars		X									
Vertical static load			X		X	X					
Locomotive front end structure			X	X						X	X
Seat structure		X						X	X		
Seat attachments	X	X						X	X		
Storage racks	X	X					X				
Equipment (general)			X		X	X				X	
Handholds							X		X		
Windscreen and partitions							X				
Maximum secondary impact speed		X									
Dynamic sled testing to assess passenger injury criteria									X		
Others	X	X					X				

Section 4 Gap Analysis

A gap analysis was completed on the available industry standards related to design and performance-based standards that aim to minimize injuries and fatalities to passengers by retaining survival space or by reducing the potential of secondary impacts between a vehicle occupant and interior components.

The rail standards literature findings were compiled and categorized into Design Standard, Structural Performance Standard, or Passenger Performance Standard. Two tables were developed to categorize structural strength (e.g., compression load and collision post) and interior fittings. Table 4 1 and Table 4-2 list the rail standards and applicability of structural strength for heavy rail and for light rail and streetcars, respectively. These standards aim to keep the structural integrity of the railcar during a crash. Rail standards for interior fittings, including seats and handholds, for heavy rail and for light rail and streetcars are listed in Table 4-3 and Table 4-4, respectively. Entries with "N/A" are not applicable to the specific railcar type, and entries with a dash indicate the standard is not a specific categorized standard.

Table 4-1 *Structural Strength Standards for Heavy Rail Vehicles — Design and Performance Standards Applicability*

Standard	Design Standards	Structural Performance	Passenger Performance
49 CFR § 238.201 to 230 for Tier I	Yes, but may require modifications for heavy rail	-	-
49 CFR § 238.401 to 429 for Tier II	Yes, but may require modifications for heavy rail	Yes, but may require modifications for heavy rail	-
ASME RT-1-2015 for Light rail (streetcars included)	N/A	N/A	-
ASME RT-2-2014 for Heavy rail	Yes	Yes	-
APTA PR-CS-S-034-99	Yes, but may require modifications for heavy rail	Yes, but may require modifications for heavy rail	-
EN 15227	N/A	Yes	-
EN 12663	Yes	N/A	-

Table 4-2 *Structural Strength Standards for Light Rail and Streetcars — Design and Performance Standards Applicability*

Standard	Design Standards	Structural Performance	Passenger Performance
49 CFR § 238.201 to 230 for Tier I	Yes, but may require modifications for light rail and streetcar	-	-
49 CFR § 238.401 to 429 for Tier II	Yes, but may require modifications for light rail and streetcar	Yes, but may require modifications for light rail and streetcar	-
ASME RT-1-2015 for Light rail (streetcars included)	Yes	Yes	-
ASME RT-2-2014 for Heavy rail	N/A	N/A	-
APTA PR-CS-S-034-99	Yes, but may require modifications for light rail and streetcar	Yes, but may require modifications for light rail and streetcar	-
EN 15227	Yes	Yes	-
EN 12663	Yes	N/A	

Table 4-3 *Interior Fittings Standards for Heavy Rail — Design and Performance Standards Applicability*

Standard	Design Standards	Structural Performance	Passenger Performance
49 CFR § 238.233 for Tier I	Yes, but may require modifications for heavy rail	-	-
49 CFR § 238.435 for Tier II	Yes, but may require modifications for heavy rail	-	-
ASME RT-1-2015 for Light rail (streetcars included)	N/A	-	-
ASME RT-2-2014 for Heavy rail	Yes	-	-
APTA PR-CS-S-006-98 Rev 2 [2006]	Yes, but may require modifications for heavy rail	Yes, but may require modifications for heavy rail	-
APTA PR-CS-S-011-99	Yes, but may require modifications for heavy rail	Yes, but may require modifications for heavy rail	-
APTA PR-CS-S-016-99	-	Yes	Yes (head injury criteria, neck injury criteria, neck forces, and chest deceleration)
EN 12663	Yes	-	-

Table 4-4 *Interior Fittings Standards for Light Rail and Streetcars — Design and Performance Standards Applicability*

Standard	Design Standards	Structural Performance	Passenger Performance
49 CFR § 238.233 for Tier I	Yes, but may require modifications for heavy rail	-	-
49 CFR § 238.435 for Tier II	Yes, but may require modifications for heavy rail and light rail vehicles	-	-
ASME RT-1-2015 for Light rail (streetcars included)	Yes	-	-
ASME RT-2-2014 for Heavy rail	N/A	-	-
APTA PR-CS-S-006-98 Rev 2 [2006]	Yes, but may require modifications for light rail and streetcar	Yes, but may require modifications for light rail and streetcar	-
APTA PR-CS-S-011-99	Yes, but may require modifications for light rail and streetcar	Yes, but may require modifications for light rail and streetcar	-
APTA PR-CS-S-016-99	-	Yes	Yes (head injury criteria)
EN 12663	Yes	-	

The tables show that there are standards currently available related to structural strength (design) and structural performance for both the railcar and its interior components that could be related to transit railcars directly or with modification. Passenger performance standards written for the rail transportation mode are limited in passenger injury criteria details. The railcar specifications, addressing passenger protection from secondary impacts, are not written for railcars, but rather in terms of requirements for interior railcar components (i.e., seats and handholds). In addition, APTA PR-CS-S-016-99 only discusses seat arrangements for commuter rail, which is not directly applicable to heavy rail, light rail, and streetcars, as commuter rail seating and interior fitting requirements are much different.

The comparison of available industry standards to meet industry needs, as identified by NTSB and other available data reports, indicates that several standards address railcar structural integrity. However, there is a gap in passenger performance standards for secondary impacts related to seats, seating configuration, and other interior fittings.

Applicability

Each standard identified was reviewed for applicability to streetcars, heavy rail, and LRVs, including standard modifications needed to make the standard/criteria applicable to rail transit vehicles. The requirements for structural strength, CEM, interior fittings, and seats were considered separately.

Structural Strength

The structural strength requirements (design-based), such as compression load and collision post, are listed in Table 4-5 along with the mode for which the standard was written. The last three columns indicate if the standard could be directly applied to rail transit vehicles and the exceptions for their applicability.

Table 4-5 *Structural Strength Regulations*

Regulation	Applicability	Type	Applicability to Heavy Rail Vehicles	Applicability to LRVs	Applicability to Streetcars
49 CFR § 238.203 § 238.205 § 238.207 § 238.209 § 238.211 § 238.213 § 238.215 § 238.217 § 238.219 § 238.223	Tier I	Design	DIRECT EXCEPTION Exception for applicability if rail line: i) With no public highway-rail grade crossing ii) On which no freight operations occur at any time iii) On which only passenger equipment of compatible design is utilized iv) On which trains operate at speed not exceeding 79 mph. Otherwise, it is directly applicable		
49 CFR § 238.405 § 238.407 § 238.409 § 238.411 § 238.413 § 238.415 § 238.417 § 238.419 § 238.423	Tier II	Design	N/A	N/A	N/A
EN 12663	Passenger rolling stock	Design	DIRECT	DIRECT	DIRECT
ASME RT-1-2015	Light rail vehicles	Design	N/A	DIRECT	DIRECT
ASME RT-2-2014	Heavy rail vehicles	Design	DIRECT	N/A	N/A
APTA PR-CS-S-034-99	Passenger rolling stock	Design/ Structural performance	Scale factor	Scale factor	Scale factor

Tier I regulations could directly apply to heavy rail, light rail, and streetcars; however, a rail mode that does not share the right-of-way with other vehicles is excluded. This exception does not extend to streetcars and LRVs, as these modes can share the road with highway vehicles. Tier II standards would not apply to rail transit vehicles.

European regulations could be directly applied to streetcar, heavy rail, or light rail, as the standard covers different rail transportation modes. The load cases are similar to those described in current U.S. regulations; however, different loads are defined for each category. The specifications for anti-climbing mechanisms are contained in EN 15227.

ASME developed two different standards for light and heavy rail vehicles. Requirements for streetcars are included in the light rail standard. Both standards define structural strength loads (such as compression strength and collision post) and CEM for each transportation mode and could be directly adopted for rail transit vehicles.

The APTA standards apply to commuter rail vehicles, so their adoption for rail transit vehicles would require a redefinition of the load magnitude.

CEM

Table 4-6 lists the standards that define CEM and indicates the standards that would need modifications to apply the criteria to rail transit vehicles. Cells that are left blank indicate the regulation or standard is not specific to that railcar mode.

Tier II federal regulations for commuter rail establish the amount of energy that each crushable zone should be able to dissipate in a collision (in general, because no impact scenario is defined),and the maximum secondary impact velocity allowed inside the car during a 30-mph collision between two identical units. For applicability to heavy rail, light rail, and streetcars, the amount of energy the structure is required to dissipate must be revised, as the mass and operational velocities differ.

European standard EN 15227 describes one collision scenario for heavy rail, four different scenarios for light rail, and two scenarios for streetcars. ASME standards prescribe two scenarios for heavy rail, three scenarios for light rail (plus two static loads to simulate a collision with a streetcar), and two scenarios for streetcars. No changes would be required to the European and ASME standards to make them applicable to rail transit vehicles.

The APTA standard states the need for CEM and survivability evaluation is based on an approximate amount of energy to be absorbed and an evaluation collision scenario to assess the acceptability criteria. The APTA recommended practice suggests some input variables and outcomes to consider but does not specify any scenario or acceptability criteria. Since the inputs are design specific, this standard is directly applicable to rail transit vehicles.

Table 4-6 *CEM Regulations/Standards Scenarios*

Regulation/ Standard	Heavy Rail	Light Rail	Streetcars	Other (needs modifications for applicability to heavy rail, light rail, streetcars)
49 CFR § 238.403				1) Amount of energy to be absorbed 2) Maximum secondary impact velocity
EN 15227 (2010)	25 kph impact between identical units	1) 25 kph impact between identical units 2) 25 kph impact against 80 t wagon 3) 10 kph impact against 129 t regional train 4) 25 kph impact against 15 t deformable obstacle	1) 15 kph impact between identical units 2) 25 kph impact against 3 t rigid obstacle	1) 36 kph impact between identical units 2) 36 kph impact against 80 t wagon 3) Max train operational speed less 50 kph ≤ 110 kph impact against 15 t deformable obstacle
ASME RT-1-2015		Impact between two identical LRVs at 1) 8 kph 2) 24 kph 3) 40 kph Impact between LRV and streetcar 1) 150 kN at vehicle centerline 2) 100 kN corner load	Impact between two identical streetcars at 1) 8 kph 2) 24 kph	
ASME RT-2-2014	Impact between two identical trains at 1) 24 kph 2) 40 kph			
APTA PR-CS-S-034-99 Rev 2 [2006]				According to CEM and collision survivability plan

Interior Fittings

The standards also include criteria for railcar interior fittings, which are features inside the car such as seats, luggage racks, and handholds. Seats are treated as a separate category in this report. Specifications for interior fittings other than seats are listed in Table 4-7. Blank cells indicate the regulation or standard is not specific to that railcar mode.

Table 4-7 *Interior Fittings Standards Load Cases*

Standard	Heavy Rail	Light Rail	Streetcars	Other (requires modifications for heavy rail, light rail, and streetcars)
49 CFR § 238.233				1) 8g longitudinal 4g vertical 4g lateral
49 CFR § 238.435				1) 8g longitudinal 4g vertical 4g lateral 2) Power car control cab 12g longitudinal 4g vertical 4g lateral
EN 12663 (2010)	3g longitudinal 1g lateral (1±c)g vertical	2g longitudinal 1g lateral (1±c)g vertical	2g longitudinal 1g lateral (1±c)g vertical	5g longitudinal 1g lateral (1±c)g vertical
ASME RT-1-2015	5g longitudinal 2g lateral 3g vertical			
ASME RT-2-2014		5g longitudinal 2g lateral 3g vertical	5g longitudinal 2g lateral 3g vertical	
APTA PR-CS-S-006-99 Rev 2 [2006]				1) Luggage rack: a) 8g longitudinal 4g lateral 4g vertical b) ≥250 lbs. concentrated load at midway between supports c) ≥120 lbs. distributed load for door latches 2) Handholds: a) 8g lateral b) 500 lbs. in any direction (deformation allowed) 3) Windscreen and partitions: 500 lbs. longitudinal in any direction 4) Miscellaneous: 8g longitudinal 4g lateral 4g vertical

Federal regulation 49 CFR § 238 and APTA standards were written primarily for traditional commuter heavy rail vehicles, and portions of those standards can eventually apply to mass transit heavy rail vehicles running on dedicated guideways. The European standards were written for all transportation rail modes. The ASME rail vehicle standards directly apply to mass transit mode vehicles such as heavy rail, light rail, and streetcars. The crash energy loads prescribed in each standard vary from one another and are typically expressed as a function of the mass of the component under evaluation or as a punctual force.

- Federal regulations at 49 CFR 238.233 and 238.435 prescribe the same load for Tier I and Tier II but recommend a higher longitudinal acceleration for the power car control cab.

- ASME RT-1-2015 and ASME RT-2-2014 standards require the interior fittings fixations to withstand the same loads, regardless of the transportation mode.
- The European norm, EN 12663-1 2010, prescribes different loads among the various transportation modes. The longitudinal and vertical loads shall be applied in conjunction with gravity acceleration and considered in combination with the maximum load generated by the equipment itself. The vertical loads are a linear function of the parameter 'c' that decreases from 2g at the car's end to 0.5g at the vehicle's center.
- APTA PR-CS-S-006-99 Rev 2 [2006] separates the interior fittings into four categories with different loads, expressed as acceleration or punctual force.

Generally, loads prescribed by the EN standard for heavy rail, light rail, and streetcars are lower than the loads listed by ASME standards.

Seats

Because seats can vary significantly between rail modes, seats were handled as a separate category even though they technically fall within the interior category. Federal regulations recommend the same loads for seats of both Tier I and Tier II passenger rail vehicles. ASME and European standards refer to equipment attachments in general, so the loads prescribed for seats are the same as those for the interior fittings. APTA standards differentiate criteria for passenger seats and crew seats (Table 4 8). Federal regulations and APTA standards apply to commuter rail; therefore, load (pulse) should be redefined for application to transit heavy rail, light rail, and streetcars. Blank cells indicate the regulation or standard is not specific to that railcar mode.

ASME RT-1/RT-2 and EN 12663 refer to general interior fittings of all types of rail vehicles, including transit railcars, so no modifications are necessary to apply those standards to rail transit unless future events drive revisions.

Table 4-8 *Seats Regulations/Standards Load Cases*

Standard	Heavy Rail	Light Rail	Streetcars	Other (needs modifications for applicability to heavy rail, light rail, and streetcars)
49 CFR § 238.233 49 CFR § 238.435				1) 4g lateral 4g vertical 2) 8g longitudinal triangular pulse over 250 ms + load on seatback derived from impact of 95 percentile
EN 12663 (2010)	3g longitudinal 1g lateral (1±c)g vertical	2g longitudinal 1g lateral (1±c)g vertical	2g longitudinal 1g lateral (1±c)g vertical	5g longitudinal 1g lateral (1±c)g vertical
ASME RT-1-2015	5g longitudinal 2g lateral 3g vertical			
ASME RT-2-2014		5g longitudinal 2g lateral 3g vertical	5g longitudinal 2g lateral 3g vertical	
APTA PR-CS-S-011-99 (seats of cab crew)				1) bottom cushion vertical load 2) backrest rotation (momentum) 3) armrest a) vertical downward b) horizontal 4) anti-rotation (momentum) 5) seat attachment: 8g longitudinal 4g lateral 4g vertical
APTA PR-CS-S-016-99 (passenger seats)				1) backrest: perpendicular to the seatback 2) grab handle: longitudinal 3) vertical seat strength vertical downward 4) outside and center armrests: a) horizontal b) vertical 6) footrest vertical 7) tray table vertical downward Dynamic: 8) triangular pulse, 8g max over 250 ms, different direction for forward and backward seating 9) anti-rotation test: pendulum kinetic energy 10) lateral and vertical seat attachment: triangular crash pulse max. 4g over 250 ms.

Other Industry Standards

Automotive standards research findings were reviewed to evaluate applicability to the rail industry. A few standards related to passenger performance could be applied to rail modes (Table 4-9). The passenger performance measured by biomechanical values through ATDs could be adapted to rail transit vehicles and may be useful in evaluating designs related to seats and other interior fittings.

For railcar applicability, contactable areas could be defined according to the height above the floor and top-of-rail. Different areas could be defined for potential head and knee impacts. Injury criteria for head, neck, chest, knee, and femur could be adapted to railcars. These standards could be applied to the operator console area as well as passenger seating areas.

Table 4-9 *Automotive Passenger Performance Standards Applicable to Railway*

Standard #	Load	Performance	Acceptability Criteria
FMVSS 207 Seats	Static load in longitudinal direction	Structural performance	Shall withstand the static loads
FMVSS 222 School bus passenger seating and crash protection	Dynamic load depending on seat configuration	a) Structural performance b) Passenger performance	a) Seatback force/ deflection curve b) Head injury criteria
UNECE R80 Seats and their anchorages (buses)	1) Static load 2) Dynamic load	a) Structural performance b) Passenger performance	a) No part of the seat completely detached, seat remains firmly held (even if some attachments fail), no fractures or sharp edges b) Head injury criteria, thorax acceptability criteria, femur acceptability criteria
Euro NCAP whiplash	Dynamic test (rear impact pulse)	a) Structural performance b) Passenger performance	a) Maximum seatback deflection angle b) Head rebound velocity, neck injury criteria, head restraint contact time, thorax acceleration, maximum head rebound velocity
UNECE R25 Head restraints	Dynamic	Passenger performance	Maximum head acceleration
FMVSS 201 Occupant protection in internal impact	Head form impact velocity	Passenger performance	Maximum head acceleration
UNECE R21 Interior fittings	Head form impact velocity	Passenger performance	Maximum head acceleration
Euro NCAP Knee mapping	Full scale test pulse	Passenger performance	Femur forces and knee slider

Interior Fittings

Table 4-10 describes the load condition and if the criteria should be validated by simulation, testing, or both. The acceptability criteria, also shown, are defined as:

- Design – When the criterion is related to some design feature or refers to the static strength of the component (yield stress or ultimate stress).
- Structural performance – When deformation is allowed under a dynamic load.

- Passenger performance – When the criterion is described as injury on some body segment.

Table 4-10 *Requirements for Railway Interior Fittings*

Regulation or Standard #	Load	Simulation/ Testing	Acceptability Criteria
CFR § 238.233	Static longitudinal, vertical, and lateral load	Testing	Design
CFR § 238.435	1) General static load	Testing	Design
	2) General dynamic load	Testing	Structural performance
	3) Static load for power car control cabs	Testing	Design
	4) Static load on luggage stowage	Testing	Design
EN 12663 (2010)	Longitudinal, lateral, and vertical static load	Simulation/Testing	Design
ASME RT-1-2015	Longitudinal, lateral, and vertical static load	Simulation	Design
ASME RT-2-2014	Longitudinal, lateral, and vertical static load	Simulation	Design
APTA PR-CS-S-006-98 Rev 2 [2006]	1) Longitudinal, lateral, and vertical static load for luggage rack	Simulation	Design
	2) Longitudinal and worst-case direction static load for handholds	Simulation	
	3) Longitudinal static load for windscreen and partition	Simulation	
	4) Longitudinal, lateral, and vertical static load other	Simulation	

Current federal regulation about interior fittings prescribes static load for Tier I passenger cars. The Tier II regulation specifies general static and dynamic requirements. Specific static loads are defined for luggage stowage and the power car control cab interior, while all other interior fittings must withstand the defined general static loads in the longitudinal, lateral, and vertical directions. Both regulations require testing, either static or dynamic (sled test). European standard EN 12663 and the ASME RT-1/RT-2 standards for streetcars, light rail, and heavy rail specify load condition for all equipment, while APTA PR-CS-S-006-98 Rev 2 [2006] defines different load cases for each component.

The fulfillment of the requirements listed in Table 4-10 can be demonstrated through simulation and/or testing. As the test conditions to simulate are dynamic, the simulation must be performed by means of an explicit solver in simulation software such as LS-DYNA, RADIOSS, PAMCRASH, and others. The ASME standard for light rail, the European standard, and U.S. Tier I regulations could directly apply to streetcars, light rail, and heavy rail. APTA standards refer to commuter rail; therefore, the requirements should be adapted to the other transportation modes before adoption.

Seats and Seat Layout

U.S. federal regulations for seats in Tier I and Tier II heavy rail vehicles are included in the “interior fittings requirements” (49 CFR § 238.233 and § 238.435). These regulations assess the static and dynamic structural requirements for the seat and attachment fittings. The regulations require testing to demonstrate criteria has been met. Other requirements for seats are included in the APTA standards (Table 4-11).

Table 4-11 *Requirements for Railway Seats*

<table>
<tr><th>Regulation or Standard #</th><th>Load</th><th>Testing/ Simulation</th><th>Acceptability Criteria</th></tr>
<tr><td rowspan="3">CFR § 238.233</td><td>1) Static vertical and lateral load</td><td>Testing</td><td rowspan="3">Design</td></tr>
<tr><td>2) Dynamic longitudinal load</td><td>Testing</td></tr>
<tr><td>3) Static loads for locomotive cab and floor-mounted seat in the cab</td><td>Testing</td></tr>
<tr><td rowspan="3">CFR § 238.435</td><td>1) Dynamic load</td><td>Testing</td><td>Structural performance</td></tr>
<tr><td>2) Design requirement about seat material</td><td>N/A</td><td rowspan="2">Design</td></tr>
<tr><td>3) Static load</td><td>Testing</td></tr>
<tr><td rowspan="6">APTA PR-CS-S-006-98 Rev 2 [2006] (apply to cab car)</td><td>1) Bottom cushion static load</td><td rowspan="5">Testing</td><td rowspan="5">Design</td></tr>
<tr><td>2) Backrest static load</td></tr>
<tr><td>3) Armrest vertical load test</td></tr>
<tr><td>4) Armrest horizontal load test</td></tr>
<tr><td>5) Anti-rotation test</td></tr>
<tr><td>6) Dynamic seat attachment</td><td>Testing</td><td>Structural performance</td></tr>
<tr><td rowspan="13">APTA PR-CS-S-006-98 Rev 2 [2006] (coach car)</td><td>1) Backrest strength</td><td rowspan="7">Testing</td><td rowspan="7">Design</td></tr>
<tr><td>2) Grab handle strength</td></tr>
<tr><td>3) Vertical seat strength</td></tr>
<tr><td>4) Armrest strength</td></tr>
<tr><td>5) Footrest strength</td></tr>
<tr><td>6) Leg rest strength</td></tr>
<tr><td>7) Tray table</td></tr>
<tr><td>8) Forward facing seat attachment and human injury</td><td rowspan="2">Sled testing</td><td rowspan="2">a) Structural performance
b) Passenger performance</td></tr>
<tr><td>9) Rearward facing seat attachment and human injury</td></tr>
<tr><td>10) Anti-rotation</td><td rowspan="4">Sled testing/ component testing</td><td rowspan="4">Structural performance</td></tr>
<tr><td>11) Lateral seat attachment</td></tr>
<tr><td>12) Vertical seat attachment</td></tr>
<tr><td>13) Forward facing seat attachment</td></tr>
</table>

Section 5

Data Collection of Rail Transit Equipment

From June to July 2017, State Safety Oversight Agencies (SSOAs) were asked to provide information on crashworthiness and CEM implementation in rail transit vehicles operated by rail transit agencies in their jurisdiction. The purpose of the data collection effort was to:

- Identify any crashworthiness/CEM specifications transit agencies have used or will be using in rail vehicle procurement.
- Identify any past or current transit crashworthiness/CEM specifications used for major mid-life carbody rehabilitations.
- Define and analyze the number of transit rail vehicles installed with crashworthiness/CEM equipment.

A copy of the data collection form is provided in Appendix A. Appendix B contains the responses from SSOAs, including information obtained from 31 rail transit agencies.

Rail Transit Vehicles Equipped with Crashworthiness/CEM

Data collected from the 2017 study found that of 10,781 rail transit vehicles in service, 54% have crashworthiness or CEM equipment installed (Figure 5-1). Figure 5-2 displays the breakdown of installed CEM equipment by rail transit mode, showing that 59% of heavy rail have some type of CEM design.

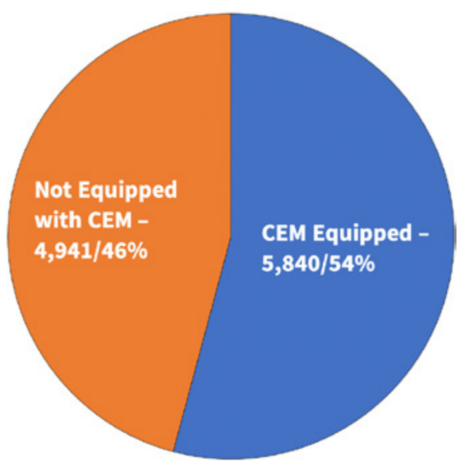

Figure 5-1 *Percent of rail transit vehicles equipped with crashworthiness components*

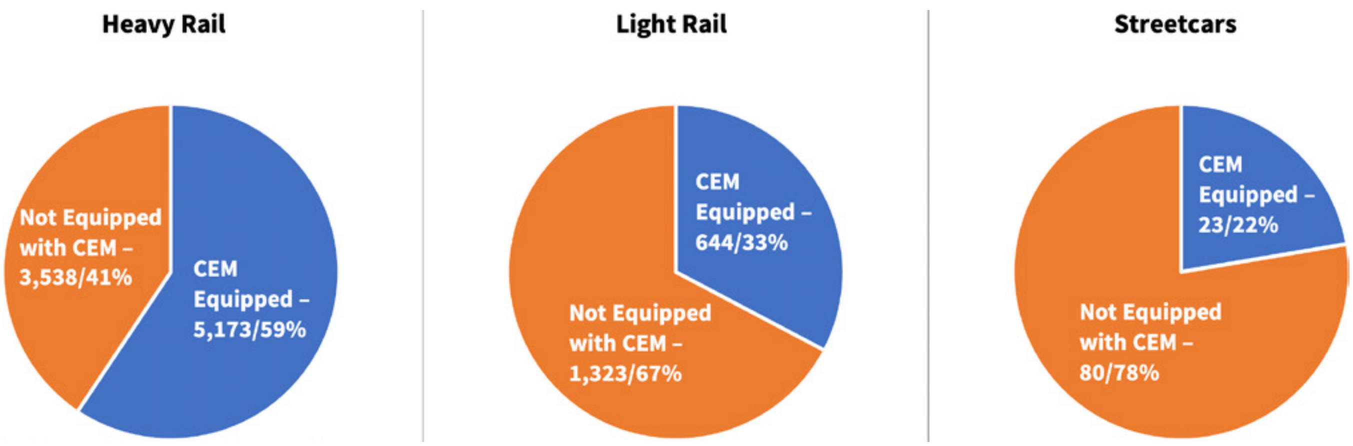

Figure 5-2 *Crashworthiness by rail transit mode*

CEM/Crashworthiness Specifications

Agencies provided the crashworthiness/CEM specifications of fleets currently in service. It is noteworthy that many transit agencies possess active rail vehicles that were purchased before the ASME standards were published. As a result, the specifications provided were internal agency documents. After reviewing agency specifications, researchers classified the specifications similarly to ASME standards for heavy rail and light rail. The internal agency specifications were compared to the ASME crashworthiness definition:

- Minimize the possibility of injury to occupants during a collision from such causes as the detachment of parts of the carbody or falling equipment mounted in the ceiling or on the roof.
- Minimize the loss of occupant volume resulting from structural collapse or structural penetration.
- Provide a progressive controlled collapse of energy absorption zones of the carbody structure.

Structural load requirements aim to address the first two points above, while CEM strategies address energy absorption requirements. CEM equipment is identified with those components that crush during an impact, thus absorbing energy. The crashworthiness components are those that could be involved in the impact but are not designed to crush or crumple. The anti-climbing mechanism itself may be singly a crashworthy component or a CEM component if the structure on which the anti-climbing front plate is attached is engineered to crush.

A review of the transit agency data indicates that some agencies claim their fleets are CEM-equipped with anti-climbing elements, while there was no evidence of CEM structural designs or components in their respective technical specifications.

The data collection effort also requested information on CEM specifications that were used in new vehicle requests for proposal and/or emerging specifications used on bids for the mid-life rehabilitation of vehicles. While none of the responding agencies have mid-life rehabilitation plans, three of the six heavy rail agencies are planning new vehicle procurements to conform to ASME RT-2-2014 for CEM new vehicle designs. Those agencies include:

- Bay Area Rapid Transit (BART)
- Los Angeles County Metropolitan Transportation Authority (LACMTA)
- New York City Transit (NYCT)

Three agencies defined other specifications used for procurement purposes as follows:

- WMATA – Indicates APTA PR-CS-S-006-98 Rev 2 [2006] as an internal agency crashworthiness specification.
- Denver Regional Transportation District (RTD) – Internal specifications for crashworthiness design
- Kansas City Streetcar – Specified EN 12663 and EN 15227

Interior Fitting Specifications

Agencies were asked if they use specification(s) to define the interior fittings of transit railcars, including seats. Two of the 31 agencies listed APTA PR-CS-S-006-98 Rev 2 [2006] for interior design. All other agencies use internal specification requirements (i.e., car builder/agency standards).

Section 6

Conclusion and Findings

CEM is a design strategy that aims to reduce passenger injuries through energy absorption and by controlling structural crush. CEM designs influence secondary impact velocities in the railway vehicle, reducing the secondary velocity of failing components affecting the occupants within the railcar.

The need to develop CEM standards for rail transit vehicles is highlighted by NTSB recommendations, including NTSB R-06006, due to several accidents[36] between 1996 and 2009. The recommendations were directed to agencies and FTA specifically to implement crashworthiness requirements for new car or major rebuild procurements. Other research reports highlight the need for crashworthiness standards, including:

- LRV crashworthiness research analyzes the injury mechanism of a passenger depending on seat layout in different energy level crash scenarios. The most common injuries are related to the head, neck, and femur. Injury criteria developed by NHTSA directly apply to interior crashworthiness analysis.
- Research on commuter and intercity trains analyzes potential strategies to reduce passenger injuries due to secondary impact. Some of the suggested strategies (such as compartmentalization) could be adopted for streetcars, light rail, and heavy rail.

A Transit Safety Standards Working Group was formed to provide guidance and industry stakeholder insight into the safety standards development process. The Working Group discussed the following topics that were not specifically referred to in the NTSB reports or other reviewed research reports:

[36] R-85-096 To the Chicago Transit Authority: Ensure that those 6,000-series cars which will be retained for service are structurally sound before they are returned to revenue service. http://www.ntsb.gov/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=R-85-096.
R-06-002 To the Washington Metropolitan Area Transit Authority: Either accelerate retirement of Rohr-built railcars, or if those railcars are not retired but instead rehabilitated, then the Rohr-built passenger railcars should incorporate a retrofit of crashworthiness collision protection that is comparable to the 6000-series railcars. http://www.ntsb.gov/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=R-06-002.
R-06-006 To the Federal Transit Administration: Develop minimum crashworthiness standards to prevent the telescoping of transit railcars in collisions and establish a timetable for removing equipment that cannot be modified to meet the new standards. http://www.ntsb.gov/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=R-06-006.
R-12-039 To the Federal Railroad Administration: Develop side impact crashworthiness standards (including performance validation) for passenger railcars that provide a measurable improvement compared to the current regulation for minimizing encroachment to and loss of railcar occupant survival space. http://www.ntsb.gov/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=R-12-039.
R-12-040 To the Federal Railroad Administration: Once the side impact crashworthiness standards are developed in Safety Recommendation R-12-39, revise 49 Code of Federal Regulations 238.217, "Side Structure," to require that new passenger railcars be built to these standards.
R-15-001 To the Federal Railroad Administration: Revise Title 49 Code of Federal Regulations (CFR) 238.213 to require the existing forward-end corner post strength requirements for the back-end corner posts of passenger railcars. http://www.ntsb.gov/_layouts/ntsb.recsearch/Recommendation.aspx?Rec=R-15-001.

- Implementation of crashworthiness standards similar to those published by ASME or EN is just beginning due to the recent publications of the standards, the extended useful life of rail transit vehicles, and the length of time required for new rail transit vehicle procurement.
- An agency procuring new fleets equipped with CEM indicated that the ASME standard for corner posts required a redesign related to the operator line-of-sight for operation.
- A member of the Transit Safety Standards Working Group, whose transit agency is procuring new fleets equipped with CEM, noted that the agency's specifications call for modular CEM components that can be replaced if damaged or if newer or better technology becomes available.
- Agencies with only some of their fleet equipped with CEM components should evaluate the interoperability of CEM-equipped vehicles with non–CEM-equipped vehicles and the effects mismatched equipment could have in a crash.

CEM standards currently available for rail transit use include European and ASME standards. The standards developed by APTA apply to commuter rail and cannot be directly adapted to rail transit vehicles without modifications. However, the APTA standard for seat testing to evaluate crashworthiness uses passenger injury criteria. Although commuter rail vehicles are different from streetcar, light rail, and transit heavy rail vehicles, seats are structurally independent, thus seat crashworthiness testing for transit vehicles could use the passenger injury criteria standard.

Several existing standards, with or without modifications, could directly address structural performance for light rail, streetcars, and heavy rail transit cars. Rail passenger performance standards do not address biomechanical limits. Injury criteria, including biomechanical limits for evaluating passenger performance are extensively used in the automotive industry and could be directly applied to the rail industry because the standards are structurally independent. Biomechanical limits are limits for survivability related to head acceleration, head injury, chest compression, and other factors.

A transit industry data collection effort was completed to investigate the implementation of CEM components for transit railcars and the standards used. The data collection effort requested that SSOAs provide information from the rail transit agencies in their representative states. SSOA responses represented data for 31 rail transit agencies. Analysis of the data shows that CEM-equipped rail transit vehicles represent almost 54 percent (5,840 railcars) of these agencies' existing fleets (10,781 railcars). Breaking down the data by transportation mode, CEM-equipped vehicles represent 59 percent of their heavy rail vehicles (5,173), 33 percent of their LRVs (644), and 22 percent of their streetcars (23). Responses to specific questions included the following:

- Some streetcars were designed according to EN 15227 and EN 12663 due to the adoption of the vehicles from the European market. All the other vehicles were designed according to internal agency standards.
- Six rail transit agencies have plans for procuring new vehicles. The specifications that will be used for the new vehicles are:
  - ASME RT-2-2014 Safety Standard for Structural Requirements for Heavy Rail Vehicles
  - EN 12663 Structural requirements of railway vehicle bodies, and EN 15227 Crashworthiness requirements for railway vehicle bodies (2010 or subsequent approved revisions)
  - APTA PR-CS-S-006-98 Rev 2 [2006] Standard for the Design and Construction of Passenger Railroad Rolling Stock will be used as a specification for the new WMATA 8000 Series railcars.

Based on the research results and feedback and suggestions of the CUTR Transit Safety Standards Working Group, several findings are provided:

- Finding 1: ASME RT-1-2015 and ASME RT-2-2014 standards present new procurement crashworthiness/CEM guidelines.
  - The ASME RT-1-2015 and ASME RT-2-2014 standards specify the crashworthiness and structural CEM components to reduce injuries and fatalities from the primary collision.
  - The rail transit industry has begun implementing ASME rail transit crashworthiness standards.
  - The data collected from 31 rail transit agencies reveals that 55 percent of their rail transit vehicles have various types of crashworthiness equipment installed, spanning from anti-climbing crush elements to replaceable crushable components and structural crumple zones. Many of the vehicle designs utilize equipment specified by individual agencies or delivered by car builders rather than equipment that meets the existing industry standards referenced in this report.
- Finding 2: There are interior vehicle designs for new and rehabilitation procurements, including passenger seating devices, attachments and tracking/anchorages, and seatback designs, that minimize passenger secondary impacts associated with collisions.
- Finding 3: There are risks associated with the collisions of CEM-equipped revenue rail vehicles interacting with non–CEM-equipped rail vehicles as identified by FTA research and real-world incidents.
  - Implementation of CEM equipment will continue to grow as rail transit vehicles are retired.
  - Industry standards development will continue to progress to meet the challenges of designing railcars across various mass transit modes.

Appendix A Crashworthiness Data Collection Form

Crashworthiness of Newly-Constructed and Older Rail Transit Vehicles

Transportation Technology Center, Inc. (TTCI), with support from Center for Urban Transportation Research (CUTR) at the University of South Florida, was tasked by the Federal Transit Administration (FTA) in researching Crash Energy Management (CEM) standards for heavy rail, light rail and streetcars and assessing existing rail vehicle crashworthiness with regard to CEM. As part of this effort, TTCI is collecting data from the transit industry on vehicle structure used or owned by agencies. In particular, data regarding what specifications or designs have (or will be) used for structural safety of the vehicle (survival space) and reduction of injuries fatalities related to secondary impacts from interior fitting, seat layout, and more. If technical specifications can be provided in addition to the answers to the questions, please send them to MaryClara_Jones@aar.com.

1. Agency Name _____

2. Rail Mode(s) of operation (check applicable modes) _____

☐ Commuter Rail Service

☐ Heavy Rail Service

☐ Light Rail Service

☐ Streetcar

☐ Other (Please describe)

3. Number of rail vehicles in fleet by mode (please provide number of vehicles)

_____ Commuter Rail Service

_____ Heavy Rail Service

_____ Light Rail Service

_____ Streetcar

_____ Other (Please describe)

4. Present rail fleet:

a. Who is/are the manufacturer(s)? _____

b. Are the vehicles that your agency own and operate CEM equipped? _____

i. If YES, what CEM specifications were used in the design (please check)?

☐ ASME RT-1 Safety standard for structural requirements for light rail vehicles

☐ ASME RT-2 Safety standard for structural requirements for heavy rail transit vehicles

☐ EN 12663 Railway applications – Structural requirements of railway vehicle bodies

☐ EN 15227 Railway applications – Crashworthiness requirements for railway vehicle

☐ Other (please name)

ii. Can you provide the technical specifications from question ‘i’ above (if yes, please send with form)?

iii. If YES, how many vehicles in your fleet are equipped with CEM?

☐ Commuter Rail Service

☐ Heavy Rail Service

☐ Light Rail Service

☐ Streetcar

☐ Other (Please describe)

iv. If NO, is your agency planning to retrofit any of your rail vehicles with CEM components?

1. If Yes to ‘iv’, what technical specifications will be used for the retrofit?

☐ ASME RT-1 Safety standard for structural requirements for light rail vehicles

☐ ASME RT-2 Safety standard for structural requirements for heavy rail transit vehicles

☐ EN 12663 Railway applications – Structural requirements of railway vehicle bodies

☐ EN 15227 Railway applications – Crashworthiness requirements for railway vehicle

☐ Other (please name)

v. For both cases, how would CEM equipment effectiveness be assessed for your agency?

☐ Modeling

☐ Testing

☐ Combination of modeling and testing

c. Are the vehicles that your agency owns designed with specific strategy for the internal layout to minimize injuries from secondary impacts (compartmentalization, interior fitting specifications)?

i. If YES, what specifications was internal layout referring to? Can you provide the technical specifications?

☐ APTA-PR-CS-S-006-98, Rev. 1 Standard for Attachment Strength of Interior Fittings for

☐ Passenger Railroad Equipment

☐ APTA-PR-CS-S-016-99, Rev. 2 Standard for Passenger Seats in Passenger Rail Cars

☐ Other (please name)

ii. If YES, was simulation or testing performed to assess the effectiveness of internal layout requirements?

☐ Modeling Only

☐ Testing Only

☐ Combination of modeling and testing (please provide detail on what combination of both)

5. New vehicles:

a. Is your agency in the process of procuring new vehicles?

i. If YES and the procurement selection has concluded, who is the manufacturer?

ii. If YES, what specifications were used for the CEM design?

☐ ASME RT-1 Safety standard for structural requirements for light rail vehicles

☐ ASME RT-2 Safety standard for structural requirements for heavy rail transit vehicles

☐ EN 12663 Railway applications – Structural requirements of railway vehicle bodies

☐ EN 15227 Railway applications – Crashworthiness requirements for railway vehicle

☐ Other (please name)

iii. If YES, what is the specification for internal layout design (if any)? Can you provide the technical specifications?

iv. If YES, was simulation or testing performed to assess the effectiveness of CEM and internal layout requirements?

CEM

☐ Modeling Only

☐ Testing Only

☐ Combination of modeling and testing (please provide detail on what combination)

Internal Layout

☐ Modeling Only

☐ Testing Only

☐ Combination of modeling and testing (please provide detail on what combination)

Please provide contact information in case TTCI has any technical questions regarding the specifications:

Name: _____

Phone: _____

Email: _____

Appendix B: Responses to Data Collection Form

	Current Fleet			CEM Equipped		
	Heavy Rail	***Light Rail***	***Streetcars***	***Heavy Rail***	***Light Rail***	***Streetcars***
Bay Area Rapid Transit (BART)	669			669		
Los Angeles County Metropolitan Transit Authority (LACMTA)	104	251				
North County Transit District (NCTC)		12			12	
Denver Regional Transportation District (RTD)		172			172	
Santa Clara Valley Transportation Authority		99				
Memphis Area Transportation Authority			6			
Rock Region Metro-Arkansas Metro Streetcar			5			
Sacramento Regional Transit District		97				
Kenosha Area Transit			7			
St. Louis Metrolink		87				
ACI - Herzog J.V.	74			74		
Utah Transit Authority		114	3			
San Diego Trolley, Inc. (SDTI)		128				
Washington Metropolitan Area Transit Authority (WMATA)	1,098			734		
Kansas City Streetcar			4			4
Dallas Area Rapid Transit (DART)		163	4			
Hampton Roads Transit (HRT)		9				
MTA NYC Transit	6,396			3,696		
Niagara Frontier Transportation Authority		27				
Southwest Ohio Regional Transit Authority - Cincinnati Bell Connector (SORTA)			5			5
Seattle Streetcars			10			6
Sound Transit		62				
PAAC Port Authority of Allegheny County		87			87	
Southeastern Pennsylvania Transportation Authority (SEPTA)	370	159				
City of Tucson (Sun Link Streetcar)			8			8
Metropolitan Transit Authority of Harris Co.		76			76	
TriMet (Oregon)		145			18	
Tacoma Link, Sound Transit			3			
Valley Metro		50			50	
Honolulu Authority for Rapid Transportation		80			80	
San Francisco Municipal Railway		149	48		149	

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Washington, DC 20590
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