1. Introduction

Crashworthiness standards for streetcar / light rail / tramway vehicles (referred to collectively as “light rail” vehicles) have evolved significantly over time, providing important advances in safety. This evolution continues into the present day.

The purpose of the paper is to examine:

- The overall evolution of rail vehicle structural and crashworthiness standards
- ASME RT-1 overview and the safety benefits of CEM
- Equivalent vehicle crashworthiness and structural Euro Norms, and a comparison with ASME RT-1 requirements
- Recent updates to ASME RT-1
- Obstacles to the wider application of ASME RT-1

The authors conducted a literature survey, and utilized personal experience and collaborative information exchange with suppliers and users of the technology to develop this paper.

2. Evolution of crashworthiness standards

2.1 First era (pre 1952): The Golden Age of Streetcars

For quite some time there were no structural standards or crashworthiness requirements for streetcars / interurbans (early equivalent to light rail). Although the American Electric Railway Association and its successors were quite active specifying components and other safety standards, carbody requirements tended to be limited to practical considerations such as coupler and anti-climber / bumper heights. Early carbodies were made entirely of wood, evolving from being horse / cable drawn to having electric propulsion, then moving to steel underframes as capacities and speeds increased, eventually becoming entirely made of steel and other metals in the PCC era. During this time, US firms exported streetcar / interurban vehicles, components and technology to the world.

Heavy rail in the US evolved similarly from wood to steel carbodies, but adopted uniform structural standards originally promulgated by the Railway Mail Service, and later the American Association of Railroads and then the Federal Railway Administration.
2.2 Second era (post 1952): The Wilderness Years

By the early 1950s, most of the US streetcar and interurban systems had been abandoned and the US effectively withdrew from further development of streetcar / interurban technology, while many countries in Europe (in particular, Germany) continued to develop the technology.

2.3 Third era (1972): UMTA US Standard LRV Development

By the 1970s, two of the handful of remaining streetcar systems, Boston and San Francisco, were in urgent need of new vehicles. In 1972 the US Department of Transportation’s Urban Mass Transit Administration (UMTA) sponsored the development of a new Standard Light Rail Vehicle (SLRV) design in cooperation with eight transit authorities and two consulting firms to meet this need. For the first time, vehicle end to end buff strength (but still not crashworthiness) was specified as follows:

“Under the combined maximum vertical load and an end load, applied horizontally at the end sills, equivalent to 2g (two times the actual empty car weight).... stress in the principal framing members shall be not greater than the yield point of the material.”

Despite extensive research into this question, no supporting documentation for this requirement has been located to date. It should be noted that European practice at this time concentrated on collision avoidance and required far lower buff strength.

In 1981, again under UMTA sponsorship, this vehicle specification was updated and issued as UMTA-MA-06-0025-81-4, the Light Rail Transit Car Specification Guide, which became the basic light rail vehicle technical specification format, along with many of the requirements still used today. In this guide, crashworthiness was addressed for the first time in the US as follows:

“2.1.2 Crashworthy Design Requirements. All systems shall be designed in the most restrictive ambient conditions and assuming maximum power supply tolerances (“worst case” design)

The following guidelines are suggested to achieve crashworthy design goals for front end collisions of empty cars:

Baseline – Vehicle ends to withstand 2.5 mph impact with solid object and sustain zero damage.

Vehicle ends to withstand 10 mph impact with solid object with permanent deformation confined to forward two feet and damage confined to forward four feet of vehicle, measured from extreme end of car, and with no hazardous high voltage electrical damage. Said damage shall be repairable without replacing structural or electrical parts, including wiring, aft of these four feet of damage.

Option 3 (Couplers) – Vehicle ends to withstand 2.5 mph impact with solid object and sustain zero damage.

Vehicle-ends to withstand 5.0 mph impact with damage confined to energy absorbing elements in the draft gear assembly.
Vehicle ends to withstand 10 mph impact with solid object with permanent deformation confined to forward two feet and damage confined to forward four feet of vehicle, measured from extreme end of car, and with no hazardous high voltage electrical damage. Said damage shall be repairable without replacing structural or electrical parts, including wiring, aft of these four feet of damage.

Verification of the extent to which crashworthy design goals have been achieved shall be accomplished either by actual specimen tests or by analysis.

The ends of the car body shall incorporate an anti-climb feature of such design that in accidental contact between cars, Option 3 – when couplers are not engaged or when the impact force is sufficient to release draft gear, the anticlimb elements will mate to prevent understructure override or telescoping and allow energy distribution (See paragraph 3.7.1)”

However, in the same guide, under section 2.3.1.3 Vehicle Systems Testing, a) Carbody Compression and Vertical Load:

“(5) A test load of 110% of the draft gear collapse force shall be applied to the coupler fixation base plate by means of a ram. In a similar manner, a test of equal to 1.8 g (1.8 times the actual empty car weight) shall be applied to the anticlimber at the longitudinal centerline of car over an area not to exceed six inches high by twelve inches wide.”

Despite these two federally supported documents, the 2g buffload requirement never became a national standard and it was not used by all authorities. However, the California Public Utilities Commission (CPUC) codified this requirement for light rail systems operated in the state of California after January 1, 1979 under CPUC General Order 143, Safety Rules and Regulations Governing Light-Rail Transit, first adopted in June 1978. The latest version, CPUC General Order 143-B: 2000 currently states:

“6.03 STRENGTH OF MAJOR STRUCTURAL COMPONENTS. Every LRV shall be designed and constructed so that all major structural components meet or exceed the following standard:

Under the action of an end compression load equal to twice the weight of the unloaded LRV applied longitudinally at the end sills, there shall be no permanent strain in any structural member and there shall be no stress in any such member exceeding the yield strength or yield point of the material. This standard shall apply for both the conditions of a fully loaded LRV and an unloaded LRV.”

In 1978 when CPUC created GO143, there were only seven light rail / streetcar systems still operating in the US. It is also notable that this pre-dated the advent of modern low-floor vehicles (which debuted in Europe in 1984). However, due to the large LRV fleets operating in California and the local presence of several major vehicle suppliers, the 2g requirement became enshrined in light rail vehicle specifications and designs for the majority of other fleets in the US, making it the defacto national standard.

2.4 Fourth era (1995): ASME RT Standards Development

Not everyone was content with just adopting the 2g requirement, recognizing the lack of any true national structural standard and the lack of any real commitment to providing crashworthiness
attributes in new light rail vehicle specifications, even though this had become standard for road vehicles.

2.4.1 Setting the Stage

In 1995, with the construction of the new Hudson Bergen light rail line (HBLRT) under a DBOM contract and the extension / modernization of the Newark City Subway (NCS) then being planned by New Jersey Transit (NJT), it was clear a number of new, 70% low floor, high capacity light rail vehicles would be required. With an eye towards achieving the potential benefits of lower weight, lower energy costs and higher levels of safety, a new, progressive structural and crashworthiness approach was adopted when specifying the vehicles. In particular, the vehicle technical specification required:

“3.3.3 End Sill
Compression buff load of 392 kN (88,000 lb.) under AW4 vertical load. No permanent deformation of any structural member or sheathing.

3.3.4 Coupler Bracket
Coupler bracket compression of 432 kN (97,000 lb.) under AW4 load. No permanent deformation of any structural member or sheathing.

3.3.12 Crash Energy Management

a. Each car end shall be designed to absorb 308 kJ of energy adequately distributed between the energy absorber of the coupler, anticlimber with energy absorber, and the end of the underframe structural elements.

b. The end of underframe structure controlled collapsing travel shall be between 600 to 1000 mm (23.6 to 39.4 inches) and shall be able to absorb 208 kJ (145,000 foot lb.) of energy.

c. The crash energy management scenario is based on the assumption that a two-car train collides with another two-car train which is not braked, at a closing speed of 20 km/h (12.5 mph). Each car weighs 392 kN (88,000 lb.).

d. The car structure shall be constructed in such a way as to minimize the possibility of injury to occupants from such causes as the detachment of parts of the body structure and the formation of large jagged fracture edges.

e. The passenger compartment shall have no sharp corners, edges, or locations which may present a hazard during a collision.

f. Seat frames and grab handles shall provide adequate padding, protection and resilience.”

These requirements were used as the basis for the initial order of 45 vehicles, the first in the US to incorporate lower buff strength (non-2g) and crashworthiness features. Today that pioneering combined fleet numbers 107 cars.
To provide a comparison as to just how different these requirements were at that time, typical light rail vehicles of that time had an average tare weight of around 100,000 lbs. A representative 2g buff load would then be around 890 kN (200,000 lbs) as compared to 392 kN (88,000 lb.) for the new cars.

In 1997, the Transit Cooperative Research Program (TCRP) under the sponsorship of Federal Transit Administration (FTA) issued *Synthesis of Transit Practice 25 – Light Rail Vehicle Compression Requirements* which documented then current practices in the US, Europe and Japan in regards to vehicle carbody buff strength.

This study found that US compression requirements were two to four times those in Europe. This was to some degree due to the fact that the agencies in the US tended to operate longer trainsets at higher speeds than their European counterparts.

In addition they also concluded that:

- “LRV compression resistance is only one measure to be considered in protecting passengers from the effects of a collision. Other measures include car-end energy absorbers, collapsible vehicle ends, effective brakes, softly padded interiors, automation of selected components of operation and drivers training."

- Compression resistance, when gradually increased, reaches a point beyond which its further increase is no longer beneficial to the vehicle.

- Although 2g may be appropriate for larger vehicle consists and higher speeds, statistics show that in some circumstances, absolutely safe operations are conducted with vehicles built to compression requirements as low as 0.5g.

- The potential benefits from lower compression load are lower vehicle weight, less wear of vehicle subsystems and components, lower energy consumption, reduced capital and operating costs, and greater safety resulting from energy being absorbed by the car ends when a controlled crash is allowed in high-energy frontal impacts.”

### 2.4.2 Creation of the ASME RT Standards Committee

In 1999, the ASME created the RT standards committee whose remit was to address the lack of a national standard relating to light rail vehicle carbody structural strength and crashworthiness. Given that the automotive industry had already been providing collision energy management (CEM) features for more than two decades, this was a timely, if not long overdue development. The standards developed for the NJT Hudson Bergen project became the starting point for the new standard, RT-1 *Safety Standard for Structural Requirements for Light Rail Vehicles*.

However despite a growing body of evidence relating to the demonstrated benefits of lower buff strength rail vehicles with CEM features in Europe, gaining consensus on a new standard proved difficult. This was primarily due to the mandatory 2g requirements adopted by the California Public Utilities Commission (CPUC) in General Order 143-B, which by this time had resulted in very large fleets of 2g rated light rail vehicles being placed into revenue service not just in California, but nationwide.
Concerns were also expressed regarding the proposed reductions in buff strength and about collisions between LRVs built to different crashworthiness standards (e.g. RT-1 compliant versus the traditional 2g design). Over the following 10 years of initial development, over a dozen drafts of the proposed new standard were issued for comment.

In 2003, the technical requirements for the new Phoenix light rail vehicles utilized draft 5 of ASME RT-1, which included CEM requirements similar to those of the NJT Hudson Bergen vehicles, but also added further safety enhancements of energy absorbing bumpers, folding auto-couplers and a fully enclosed front end. These 50 vehicles were the first vehicles to apply the new ASME RT-1 standard and have an exemplary record of preventing injury and death.

Eventually in 2009, ASME RT-1-2009 was approved and officially released as a national streetcar and light rail vehicle structural and crashworthiness standard.

### 2.4.3 RT-1 Highlights

For those experienced in developing vehicle technical specifications, much of this standard will be familiar, though with many elements are now much more clearly defined and comprehensive. RT-1 also covers the crashworthiness requirements for passive safety features to “enhance occupant safety and control damage” in addition to the more traditional structural requirements.

**Core CEM principles:** The standard clearly emphasizes the protection of vehicle occupants, stating that “the carbody shall be constructed in such a way as to:

- minimize the possibility of injury to occupants during a collision from such causes as parts detaching from the carbody or equipment falling from the ceiling or roof
- minimize the loss of occupant volume resulting from structural collapse or structural penetration
- provide for a progressive controlled collapse of energy absorption zones of the carbody structure while limiting the average longitudinal acceleration"

**Leading End Design:** To improve pedestrian and road traffic safety, the vehicle front end design must be more incident friendly, requiring a full-enclosed front end with a smooth, contoured geometry designed to deflect rather than entrap people or objects.

**Progressive Collapse / Energy Absorption Zones:** The standard describes structural energy absorption zones and the requirement to function in sequence (i.e., the initial impact energy shall be fully absorbed by Zone 1 prior to the absorption of impact energy by Zone 2):

- **Collision Zone 1:** Designed to absorb impact energy in the event of a relatively low-severity frontal collision with another LRV or streetcar with a closing speed of 8 km/hr (5 mph).

- **Collision Zone 2:** Having consumed the energy in Zone 1, this zone accommodates collisions between two single like LRVs or streetcars with a closing speed of 24 km/hr (15 mph).
Collision Zone 3: (Applicable to Light Rail Vehicles Only) Having consumed the energy in Zones 1 and 2, this zone is intended for higher-speed collisions to absorb the additional energy associated with collisions between two single like LRVs at a closing speed of 40 km/hr (25 mph).

Operator Protection: The standard includes specific protections for the operator, including an operator’s cab door and seat designed to allow quick emergency egress.

Structural Load Cases: At the heart of this standard are two tables which define the various structural load cases and collision scenarios which must be met. The remainder of the standard covers structural, linear-elastic stress and crashworthiness analysis, as well as testing. For the purposes of comparison with other standards, the carbody end sill buff loads specified are:

- Light rail vehicles: 400 kN
- Streetcars: 300 kN

2.4.4 Development of Euro Norms

During those same 10 years, European operators developed two new companion Euro Norm standards covering the same subject area as ASME RT-1:

- EN 12663-1 (first released in 2000, current revision is 2010) Railway Applications—Structural Requirements of Railway Vehicle Bodies to address vehicle structural requirements. It covers all categories of rail vehicles, including locomotives, passenger vehicles and freight wagons.
- EN 15227 (first released in 2008, currently undergoing review for revision) Railway Applications—Crashworthiness Requirements for Railway Vehicle Bodies, based on similar CEM principles as RT-1, but covering all categories of rail vehicles, from locomotives and coaches, metro vehicles, tram-trains and peri-urban trams to tramway vehicles, each with their own specific crashworthiness requirements.

Given that European designs built to these standards dominate the global market for light rail and streetcar type vehicles, and the US buys only a relatively small portion (<15%) of the global production of such vehicles from a modest number of international carbuilders, in order to obtain vehicles requiring the lowest level of redesign and thus ultimate cost, it is important to understand the differences between these standards and ASME RT-1.

2.4.5 EN 15227 Crashworthiness Highlights

EN 15227 emphasizes the importance of considering crash avoidance in conjunction with passive safety requirements, noting that they are intended as “the last means of protection when all possibilities of preventing an accident have failed.” Like RT-1, it also emphasizes protection of vehicle occupants, and explains how the document is to be used together with the companion EN 12663 structural requirements:

“The static compression load requirements on the vehicle ends, required by EN 12663, are intended to provide a basic structural integrity to the occupied areas in a collision-type accident.
This European Standard adds to the basic strength requirement by setting additional requirements for structural passive safety in order to increase occupant safety.”

As noted earlier, this standard classifies the railway vehicle into one of four categories depending on the type of operation and vehicles generally associated with each. For the purposes of this paper, two of these categories are generally applicable, namely:

- **Category C-IV**: Light rail vehicles designed to operate on dedicated urban networks interfacing with road traffic (tramway vehicles)
- **Category C-III**: Light rail vehicles designed to operate on urban and/or regional networks, in track-sharing operation, and interfacing with road traffic (Tram trains, peri-urban tram)

At first glance it would appear that Category C-IV corresponds to Streetcars, while Category C-III corresponds to Light Rail, but one must take great care when allowing the use of Euro Norm equivalents to RT-1 that the correct category of vehicle is utilized as they do not exactly correspond.

This standard sets out four collision scenarios which vary depending on the category:

“The design collision scenarios specified below are not the only cases occurring on the infrastructure of public rail transport in Europe, but they represent the most common collision situations and those that result in most of the casualties.

1) A front end impact between two identical train units;
2) A front end impact with a different type of railway vehicle;
3) Train unit front end impact with a large road vehicle on a level crossing;
4) Train unit impact into low obstacle (e.g. car on a level crossing, animal, rubbish).”

However, if operational conditions are such that a design collision scenario cannot occur or has a very low risk of it occurring, there is no need to consider that collision scenario.

To illustrate the importance of establishing the right EN 15227 category, the train to train collision speeds in this standard are 15 km/hr for Category C-IV vehicles (versus 24 km/hr for Collision Zone 2 RT-1 streetcars and light rail vehicles) and 25 km/hr for Category C-III vehicles. Note also that the collision scenarios in RT-1 and EN 15227 do not directly correspond (no equivalent to Collision Zone 1 or Zone 3 requirements of RT-1), nor is the crashworthiness acceptance criteria the same.

**2.4.6 EN 12663-1 Structural Requirements Highlights**

The companion structural norm, EN 12663-1, covers the full spectrum of rail vehicles as noted earlier, and also uses different vehicle category classifications than EN 15227. The two categories that are roughly equivalent to US Streetcar and Light Rail vehicles are:

- **Category P-V**: Tramway vehicles
- **Category P-IV**: Light duty metro and heavy duty tramway vehicles

To re-iterate, one must take great care when allowing the use of Euro Norm equivalents to RT-1 that the correct category of vehicle is utilized. A critical difference here relates to the end sill compression...
requirements, where the required loads are 200 kN for Category P-V vehicles (vs. 300 kN for RT-1 streetcars) and 400 kN for Category P-IV vehicles (same as RT-1 light rail vehicles).

Similar to RT-1, the standard covers vertical loads, end sill compression, body to truck attachment, and equipment attachment, as well as setting out the methodology for analysis and validation. However it does not cover coupler loads, collision post / end wall loads, side wall loads or roof loads. It does contain other requirements not covered by RT-1 (which focuses solely on safety issues), including articulation joints, lifting and jacking, and fatigue load cases.

As a general observation, when examining the revisions of the various documents over time, the European and US CEM requirements for streetcars and light rail vehicles have been converging, but there are still some significant differences.

2.5 Fifth era (current day)

As with any national standard, a periodic review of the standard to ensure its continued relevance is required. In 2015, RT-1 was duly reviewed by the ASME and a revised version ASME RT-1-2015: Safety Standard for Structural Requirements for Light Rail Vehicles has now been issued with important changes being incorporated that move it closer to the requirements of the equivalent Euro Norms noted above, but there still remains a great deal of difference in the details.

Significant revisions in the 2015 version of RT-1 include:

- Splitting the two tables of load requirements into separate structural and crashworthiness load tables for each vehicle type, namely:
  - Table 1: Structural Load Requirements for LRVs
  - Table 2: Structural Load Requirements for Streetcars
  - Table 3: Crashworthiness for LRVs
  - Table 4: Crashworthiness for Streetcars

- Vehicle passenger loading is no longer expressed based on the conventional Assigned Weights, in particular increasing the average weight per person from 70 kg [154 lb] to 79.5 kg [175 lb] to reflect US population trends and replacing the more traditional AW0 through AW4 passenger loadings with new ready to run, seated load and car volume capacity load definitions.

- It is now required that infrequent loads such as re-railing, recovery and emergency braking are assessed to ensure damage does not occur from their application, although specific loads are not provided.

- Prescriptive load case requirements for anti-climber attachment have been removed, replaced with an overall performance requirement for anticlimber performance that establishes a maximum for wheel lift during a collision. (This approach is comparable to the performance-based anticlimb requirements in EN 15227).

- In the crashworthiness analysis, collisions between two ready to run trains (maximum number of cars used in operation) with one stationary and both with full service brakes applied must be
analyzed. (previously this was between single cars and brakes applied on only one car). Crashworthiness acceptance criteria were also further refined and expanded.

- Load cases for truck to carbody attachment were revised, adding a 178 kN transverse load.
- Collision Zone 2 and Zone 3 acceptance requirements were revised, redefining survival/crush parameters and anticlimber performance.

Although a national standard since 2009, and making a clear case for providing improved safety for both vehicle occupants and protection of other roadway users, few new rail transit vehicle procurements have actually specified ASME RT-1 during the seven years since its initial release. This is slowly changing however, and to date the RT-1 standard has been specified for use in a few new vehicle procurements including the Baltimore Purple Line, Boston Green Line and Honolulu Light Metro.

3. Conclusions

CEM principles are now embraced worldwide as the basis for crashworthiness specification in both the automotive and rail transit sectors. Both the US and Europe have developed different crashworthiness standards for railway vehicles based on CEM principles. Since the release of ASME RT-1 in 2009, this standard has evolved, with important changes being incorporated into the newest version that move it closer to the similar, but not equivalent Euro Norms (EN 12663-1 and EN 15227). This is significant given that European designs dominate the global market for light rail and streetcar type vehicles, and the US buys only a small portion (<15%) of the global production of such vehicles.

Vehicle designs built to these Euro Norms can be made equivalent to RT-1 by the utilization of the proper vehicle category, supplemented by the addition of any critical RT-1 requirements not covered by these standards.

Most importantly however, the important safety improvements represented by RT-1 and the equivalent Euro Norms are not as yet embodied in CPUC GO-143. Although this mandatory set of requirements applies only to vehicles operating in California, many other states have followed California’s lead and adopted these requirements. Further, from a commercial standpoint, the large light rail vehicle market in California directly impacts the new vehicle design process nationwide – no manufacturer wants to have two different vehicle designs. As long as there remains the yawning gap between the traditional 2g buff load rule required by GO-143 and the enhanced safety and crashworthiness requirements of both RT-1 and the international Euro Norm standards, we will continue to see vehicles built without this protection. The vital key to this is the adoption of RT-1 by the CPUC at the earliest possible opportunity.

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