Evaluation of European EMU Structure for Shared Use in the Caltrain Corridor

Revision 3

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Revision History

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Executive Summary

This report summarizes structural analyses performed in support of a Hazard Analysis and subsequent waiver petition for operation of European EMUs in a shared-use arrangement in the Caltrain Corridor. Currently, Caltrain operates a mix of FRA-compliant passenger locomotives and coaches. Caltrain intends to electrify the San Francisco-San Jose corridor, and intends to operate European EMUs and FRA-compliant locomotive-hauled passenger trains at the same time. Freight trains, operated by the Union Pacific Railroad under a trackage rights agreement, would be restricted to operating at night after Caltrain service shuts down.

The European EMUs are built to European structural and crashworthiness standards. A detailed analysis of these vehicles, submitted as a separate report, indicates that while they would not comply with a number of Federal Regulations in their current condition, modifications should be practicable to the design, such that waivers need only be sought for:

- 49 CFR 238.203 Static End Strength
- 49 CFR 238.205 Anti-Climbing Mechanism
- 49 CFR 238.207 Link Between Coupling Mechanism and Carbody
- 49 CFR 238.211 Collision Posts
- 49 CFR 238.213 Corner Posts

This report summarizes analyses performed by two European Carbuilders (Siemens and Alstom), as well as supplementary analyses performed by the Caltrain team, The Volpe Center, and other resources. Final results are formatted in such a way that they can be used as “outcomes” in mishap scenarios identified in a separate Hazard Analysis performed by the Caltrain team. In general, the scenarios are:

- Collisions at grade crossings with small and large highway vehicles
- Train-to-train collisions for various combinations of rolling stock
- Post-derailment collisions with a fixed object

This report shows that operating European EMU equipment mixed with FRA-compliant equipment in the Caltrain corridor does not present a safety risk that is any more severe than operating FRA-compliant equipment alone. It must be noted that the scenarios examined represent those that were deemed valid in the Hazard Analysis, based on the envisioned Caltrain system as a whole, recognizing the contribution of elements such as a positive train control system, improved grade crossing protection, and temporal separation with freight trains. It is not the intent of this report to prove that European EMUs are equivalent to FRA-compliant rolling stock in all ways, or in other environments. Nor does it conclude that it would be acceptable to use the two types of equipment interchangeably on other railroads.

The following measures are proposed to mitigate any risk of operating equipment under waiver:

System-wide Measures

- Positive Train Control meeting FRA regulations currently under development
- Temporal separation of freight and passenger trains
- Continuous improvement of grade crossing protection systems
- Over-dimensioned lading detection in strategic locations

Rolling Stock Measures (by procurement specification)

- EN12663 PII Compliance
- EN15227 CI Compliance with following specifics:
    - Train-to-train collision scenario with 8-car like trains (22.5 mph)
    - Truck impact speed 110 km/hr (69 mph)
- Additional train-to-train impact scenario
    - 8-car EMU at 20 mph impacts locomotive at the head of a stationary 5-car train
        - EN 15227 performance criteria for train-to-train collision apply with one exception. Strains in excess of 10 percent would be reviewed on a case-by-case basis.
- Minimum car body ultimate buff (buckling) strength of 1.3 million pounds
    - Maximum load resisted while buckling or crushing
- Show that the train-to-train impact scenarios above do not result in overriding or bypass at the impact interface (cab end) as well as at the intermediate connections within the train
- Provide calculations showing the vertical and horizontal strength of all elements acting to restrain the vehicles during such impacts
- Compliance with the FRA collision post “proxy object cart” impact requirement currently proposed for 49 CFR 238.205 Appendix F
- Calculations showing the amount of deformation of the corner structure of the rail car when the static loads prescribed by 49 CFR 238.213 are applied does not compromise the occupied space

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1. INTRODUCTION

This report summarizes structural analyses performed in support of a Hazard Analysis and subsequent waiver petition for operation of European EMUs in a shared-use arrangement in the Caltrain Corridor. Currently, Caltrain operates a mix of FRA-compliant passenger locomotives and coaches. Union Pacific operates freight trains in the Caltrain-owned corridor between San Francisco and San Jose via a trackage rights agreement. Caltrain operates passenger equipment in the Union Pacific-owned corridor between San Jose and Gilroy via a trackage rights agreement. Caltrain intends to electrify the San Francisco-San Jose corridor, and intends to operate European EMUs and FRA-compliant locomotive-hauled passenger trains at the same time on Caltrain-owned tracks in the corridor. Freight trains would be restricted to night operation north of Santa Clara after Caltrain service stops. Special provisions have been made to allow freight switching in the San Jose area during the day, maintaining adequate separation of freight and passenger trains.

The European EMUs are built to EN12663 [Ref 1] and EN15227 [Ref 2] structural and crashworthiness standards. A detailed analysis of these vehicles, reported in *Caltrain 2025 European EMU CFR Compliance Assessment Report* [Ref 3] indicates that while they would not comply with a number of Federal Regulations, all within 49 CFR Part 238 [Ref 4], in their current condition, modifications should be practicable to the design, such that waivers need only be sought for:

- 49 CFR 238.203 Static End Strength
- 49 CFR 238.205 Anti-Climbing Mechanism
- 49 CFR 238.207 Link Between Coupling Mechanism and Carbody
- 49 CFR 238.211 Collision Posts
- 49 CFR 238.213 Corner Posts

Through the course of evaluating these vehicles, it was necessary to determine the likely performance of the structures in various hazard scenarios identified in *Caltrain 2025 Preliminary Hazard Analysis Report* [Ref 5], and particularly related to the structural differences between North American and European Rolling stock.

The technical specification for Caltrain's procurement of these new vehicles, providing a waiver is granted, would contain specific requirements meant to dictate:

- Compliance with CFR's where currently non-compliant but design changes practicable
- Special design features like Crash Energy Management that have been used in this analysis to make the case for the waiver
- A combination of European and North American design standards that must be met
- A series of additional analyses and/or tests that must be performed to prove agreement with the assumptions made in the structural comparisons made in this report.

This report summarizes analyses performed by two European carbuilders (Siemens and Alstom), as well as supplementary analyses performed by the Caltrain team, The Volpe Center, and other resources. Final results are formatted in such a way that they can be used as "outcomes" in mishap scenarios identified in the Hazard Analysis. In general, the scenarios are:

- Collisions at grade crossings with small and large highway vehicles
- Train-to-train collisions for various combinations of rolling stock
- Post-derailment collisions with a fixed object

This report seeks to show that operating European EMU equipment mixed with FRA-compliant equipment does not present a safety risk that is any more severe than operating FRA-compliant equipment alone. It must be noted that the scenarios examined represent those that were deemed valid in the Hazard Analysis, based on the envisioned Caltrain system as a whole, recognizing the contribution of elements such as a positive train control system, improved grade crossing protection, and temporal separation with freight trains. This report does not seek to prove that European EMUs are equivalent to FRA-compliant rolling stock in all ways, or attempt to conclude that it would be acceptable to use the two types of equipment interchangeably on other railroads.

1.1. Terminology

For purposes of simplifying terminology in this report, any further reference to EMU is for a vehicle designed to European standards (as shown in Figure 1) and does not fully comply with the Code of Federal Regulations, Title 49 (49 CFR). Caltrain's existing fleet of locomotive-hauled trains made up of vehicles that fully comply with 49 CFR will be referred to herein as FRA-compliant trains or vehicles, as shown in Figure 2.

Figure 1 - Typical EMU Proposed for Caltrain Electrified Service

Figure 2 - Typical FRA-Compliant Trains in Operation by Caltrain

2. CURRENT OPERATION AND FLEET

2.1. Corridor and Operation

Caltrain serves the north/south corridor between San Francisco and San Jose, California, with a weekday commute service extending further south to Gilroy (Figure 3).

Figure 3 - Caltrain System Map

The route is a total of 77 miles with 33 stations, for an average distance between stations of 2.5 miles. Excluding Gilroy, the typical service is from San Francisco to Tamien (south of San Jose), which consists of 49 miles of track and 24 stations, for an average station spacing of 2.1 miles. Caltrain currently operates a 90 train-per-day schedule, six of which serve Gilroy (three northbound in the morning and three southbound in the evening). Service is mixed, with 22 express trains called "Baby Bullets" serving only 6 to 8 stations, 40 limited service trains, and 28 local trains. Limited service trains have several different profiles including limited-local and skip-stop. A five train per hour (per direction) peak schedule is maintained, consisting of alternating expresses and limiteds.

It is anticipated that by the time EMU service is introduced, ridership will require a six train per hour peak schedule. This will likely be made up of two diesel baby bullet express trains and four limited trains. Each express is followed by two limiteds. It is as-yet undetermined how many stops can be made by the limited trains. EMU performance may allow these to stop at nearly every station. There will be enough locomotive hauled bi-level equipment to meet the need for express service. Limited trains will be EMUs. When diesel equipment is out of service for periodic or unplanned maintenance, EMUs can provide express service. However, the diesel equipment will not be able to provide limited service. Thus, the spares pool must be primarily EMUs. This means that an FRA-compliant train will run between EMU trains on a headway as short as five minutes, but usually longer. During off-peak hours, as an energy saving measure, local service will be met by EMUs, likely single four-car trains, rather than the eight-car sets operated during the peak.

Maximum operating speed for the current and future operation is 79 mph.

2.2. Current Fleet

Caltrain currently operates with 20 trainsets each day. A 21st trainset is rotated into a maintenance cycle every week. In addition to this out-of-service trainset, there are spare locomotives and coaches available to rotate with vehicles in need of repair. While there are a few four-car trainsets, the norm is a five-car trainset.

2.2.1. Locomotives

Caltrain operates with 20 locomotives in service and 9 spares on any given day. A locomotive fleet summary is provided in Table 1.

Table 1 - Locomotive Fleet Summary

NUMBERS	QTY	MODEL	HP	BUILDER	YEAR BUILT	MID-LIFE OVERHAUL	30-YEAR RETIRE DATE
902-914 (b)	5	F40PH-2	3,200	EMD	1985	1999	2015
900-919	15	F40PH-2-CAT	3,200	EMD	1985-1987	1999	2015-2017
920-922	3	F40PH-2C	3,200	MPI	1998 (a)	2013	2028
923-928	6	MP36PH-3C	3,600	MPI	2003 (a)	2018	2033

A total of 20 F40PH-2 locomotives (Figure 2 typical) will reach the 30-year date around the same time that the electrification program is complete. These locomotives may be either sold as cores or kept in limited service to help transition to electric equipment. Due to the high fuel consumption rates of the gear drive HEP locomotives; these five units will be retired first.

Figure 4 - Caltrain F40PH-2 Locomotive

An additional three F40PH-2 locomotives were purchased in 1998 from Boise Locomotive (now Motive Power) in Boise, Idaho. These units are actually remanufactured equipment, with completely renewed engines, trucks, alternators, traction motors, and frames. Only major components, like the ones previously listed, were saved. Everything else was replaced, including the body. The components that were saved were brought to an 'as-new' condition through a very extensive rebuild effort. MPI predicts a useful life for this type of locomotive to be near or equal to a new unit. These units will be kept in service beyond electrification to provide Gilroy shuttle service.

The six MP36PH-3C locomotives (Figure 5) represent an evolution in the process described previously. In this model, MPI used a new frame, and the locomotive meets all of the safety standards of a new locomotive produced in 2003. These locomotives should last well into the 2030's and will pull the Baby Bullet express trains that will operate between local EMU service, and also feed the Gilroy diesel shuttle service, once electrification takes place.

Figure 5 - Caltrain MP36PH-3C Locomotive

2.2.2. Passenger Cars

Table 2 presents a summary of the Caltrain passenger car fleet. There are currently 118 cars in the fleet. The majority of the fleet is made up of gallery cars built by Nippon Sharyo, as shown in Figure 6. Just as the bulk of the locomotives are set to retire in the 2015 time frame, so are most of the coaches. A total of 52 trailers and 21 cab cars are set to retire as the electrification program is completed, leaving only 20 gallery cars and 25 bi-level coaches for service. This retirement date represents an opportunity to move away from gallery cars if so desired.

Figure 6 - Nippon Sharyo Gallery Car

Table 2 - Passenger Car Summary

NUMBERS	QTY	MODEL	SEATS	BUILDER	YEAR BUILT	MID-LIFE	RETIRE
4000-4020	21	Gallery Cab (bike)	107	Nippon Sharyo	1985	2001	2015
3800-3851	52	Gallery Trailer	142-148	Nippon Sharyo	1985-1987	2001	2015-2017
3852-3865	14	Gallery Trailer	122	Nippon Sharyo	1999-2000	2015	2030
4021-4026	6	Gallery Cab (bike)	82	Nippon Sharyo	1999-2000	2015	2030
112-116	5	Bi-level Cab (bike)	123	Bombardier	2001-2002	2016	2031-2032
117-118	2	Bi-level Cab	139	Bombardier	2002	2017	2032
119-120	2	Bi-level Cab (bike)	139	Bombardier	2008	2023	2038
219-230 (b)	10	Bi-level Trailer	148	Bombardier	2002	2017	2032
231-236	6	Bi-level Trailer	148	Bombardier	2008	2023	2038

The older gallery cars were built prior to the release of 49 CFR 238, which prescribed the requirements for buff strength, collision and corner post strength, side strength, and roof strength, among other safety requirements. Best practice dictated that these cars meet the 800,000 pound buff strength requirements, and be equipped with collision and corner posts. However, they were not designed to resist all of the loads prescribed in 238. The newer gallery cars and the Bombardier bi-level coaches shown below were designed to meet 49 CFR 238 with one exception. An additional collision post energy absorbing requirement was recently added. It is further described later in this report, and is commonly referred to as the steel coil impact test. Figure 7 shows the occupied areas of the gallery cab car. Note that the cab is in the upper front end. This space would be fitted with passenger seats in the coach. The only spot in the entire car that would not be typically occupied is the center of the car, which holds the vestibules and the stairways. These would typically be occupied by standees during crush loading conditions and when nearing a station.

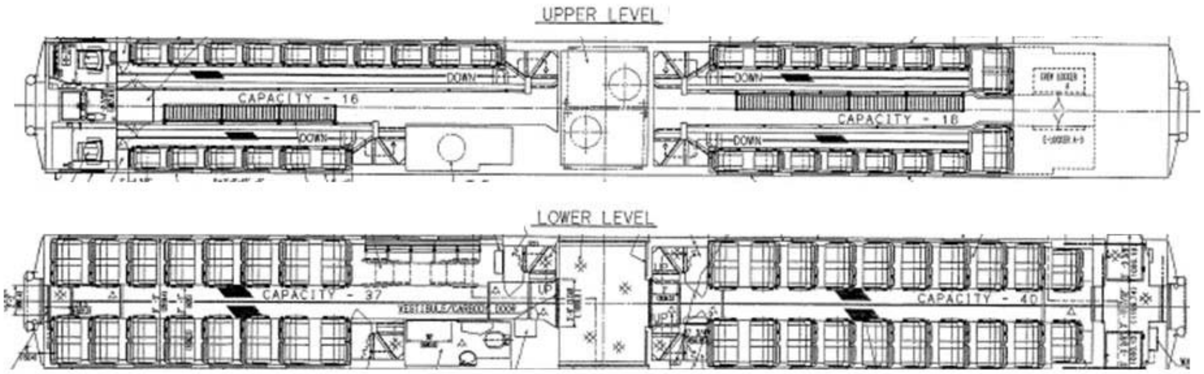


Figure 7 - Typical Gallery Cab Car Seating Layout

The Bombardier bi-level coaches, shown in Figure 8, are the newest to the Caltrain fleet. They were purchased to accommodate the Baby Bullet service. This style of railcar, with lower level floors and large doors for quick boarding, is more consistent with the future operating plan for Caltrain.

Figure 8 - Bombardier Bi-Level Cab Car and Coach

These cars were all built after the release of 49 CFR 238. The older set was built before the steel coil impact requirement was issued, but the new set was built in compliance with that regulation. Figure 9 shows a layout of the car, to indicate occupied areas. The cab is in the forward-most part of the lower level. As with the gallery cars, seating space is maximized on these cars. The only areas that would not typically be occupied would be the vestibules and the stairways leading to the various levels. These areas would be occupied during crush loading and when approaching a station.

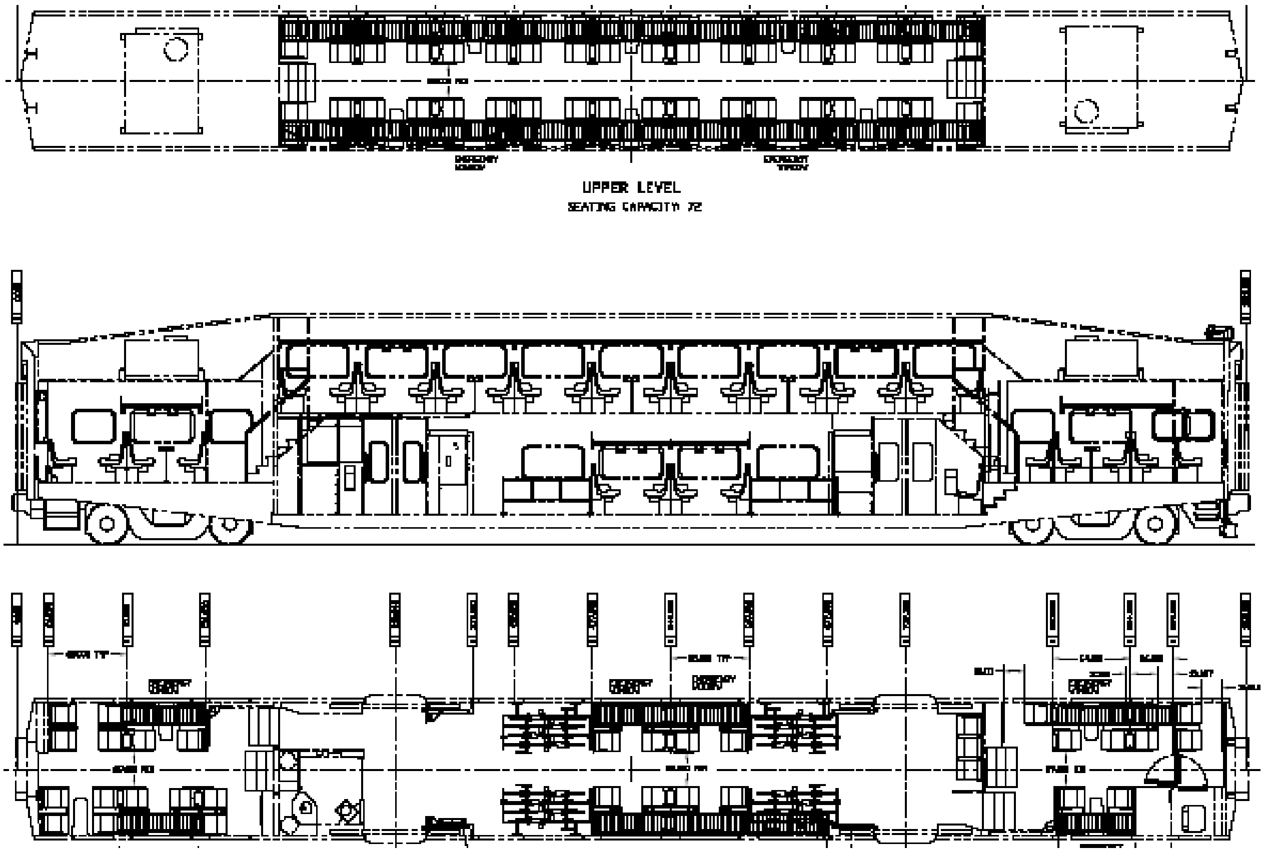


Figure 9 - Bombardier Bi-Level Cab Car Seating Layout

3. Future Caltrain Rolling Stock for Rapid Transit Service

The current Caltrain service model can be altered to provide something that looks more like rapid transit. However, it cannot be accomplished with locomotive-hauled train sets due to the less aggressive acceleration and braking rates, and train length inflexibility. Figure 10 presents a possible rapid transit concept vehicle, based on current European designs. While these vehicles are currently constructed in Europe, it is likely that, at a minimum, final assembly of the Caltrain EMUs will take place in the United States. All of the major European carbuilders have facilities in the United States, and the use of Federal funds to procure EMUs will require compliance with Buy-America requirements including a minimum percentage of American components and final assembly in the United States.

Caltrain's initial purchase would be approximately 28 4-car trainsets. This would accommodate a six train-per-hour peak schedule, with four local or limited EMU trains and two diesel locomotive-hauled baby bullet express trains. Daily fleet makeup would be 12 EMU and 6 diesel trainsets.

Figure 10 - Caltrain Rapid Transit Concept

Rapid transit is typically a higher-frequency service with self propelled vehicles, allowing train length to be varied throughout the day to most efficiently meet demand. Specific advantages of the rapid transit model are:

- Better acceleration – better trip times, fewer trains needed
- More stations served without compromising end-to-end trip time
- Lighter weight -- more energy efficient, less track wear and tear
- Train length can be shortened for off-peak operation
  - Saves energy
  - Saves maintenance
- Performance does not degrade as train length increases – distributed power
- Redundancy of propulsion systems improves reliability – distributed power.

Electrification is the first practical step toward offering rapid transit type service. North American rapid transit vehicles (more commonly known as subway cars) typically run on a third rail DC traction power system. They are also typically lighter weight and shorter in length than commuter coaches and restricted to single level designs. These single level vehicles typically have level boarding arrangements at high platforms. These rapid transit systems are typically not regulated by the FRA, due to the fact that they do not share track with any other equipment, like freight trains or heavy passenger trains. Vehicles of this sort are sometimes referred to as electric multiple units (EMUs). This refers to the ability to couple multiple self-propelled units into a train and have them controlled from one cab.

There are FRA-compliant AC EMUs in North America, which are classified as "Commuter" rather than "rapid transit", and all currently single level designs, with one exception. Chicago Metra and Northern Indiana Commuter Transportation District (NICTD) operate gallery-style EMUs, but they are powered from an overhead DC system. The term "rapid transit" is never used in conjunction with FRA-compliant cars because the FRA is not responsible for regulation of rapid transit systems by definition. Compliant EMUs are substantially heavier than rapid transit cars because they must comply with FRA structural requirements set forth in 49 CFR 238, meant to address commingling with freight equipment and increased exposure at grade crossings. This regulation requires a compressive end strength of 800,000 pounds without permanent deformation, and substantial collision and corner posts in the end walls. Given this compliance, they are allowed to share track with freight trains and other large passenger trains. A typical FRA-compliant EMU is shown in Figure 11. This is the Long Island Rail Road M7, built by Bombardier. It represents the state of the art in North American EMUs. Note that this is a third rail design, not overhead contact.

Figure 11 - Typical North American EMU

An operating scenario using FRA-compliant EMUs to replace the locomotive-hauled service was examined early in the Caltrain 2025 study. However, it did not meet Caltrain's requirements for the following reasons:

- Higher train weight limited the energy savings.
- A Single level EMU with 2x2 seating can only accommodate 90 seated passengers at best. Caltrain needs at least 100 seats to meet ridership and platform length requirements.
- High-level boarding would not accommodate existing Caltrain rolling stock and would not provide adequate clearance for Union Pacific freight trains.
- FRA-compliant multi-level EMUs do not exist today.

European railroads have begun operating double deck EMU equipment that is designed for high voltage ac overhead contact traction power. Three designs are presented here, but it is not intended to be an all-inclusive list. Caltrain will execute an open procurement, inviting all qualified proposers to participate.

Figure 12 shows the Siemens Desiro 514 double deck trainset. It is designed to be operated as a trainset, where the end units are powered, and intermediate units are not. This is similar in concept to a locomotive-hauled train, but since the trainset is integrated, equipment can be distributed in the most desirable manner, and weight can be minimized. The Siemens model is typically four cars, with a total seating capacity of about 400 passengers. Two trains can be coupled to make an eight-car train. This limits the flexibility of peak versus off-peak train length to four-car increments. Caltrain would operate eight-car trains during the peak and four-car trains during off-peak (midday and night).

Figure 12 - Siemens Desiro 514 Double Deck EMU Trainset

Alstom makes a similar model that can be as small as two cars (married pair). Figure 13 shows the Alstom Coradia Duplex. It is similar to the Desiro in many respects, but uses a slightly different distributed traction scheme.

Figure 13 - Alstom Coradia Double Deck EMU Trainset

Bombardier is currently designing a similar vehicle for Deutsche Bahn AG. It is based on a double deck push-pull design, built in the Goerlitz plant for many years. It will be service proven by the time Caltrain procures EMUs. A concept rendering is shown in Figure 14.

Figure 14 - Bombardier Multi-Level EMU Concept

These vehicles are not designed to FRA standards, thus the need for an evaluation to determine if such vehicles can safely operate in service mixed with FRA-compliant vehicles.

3.1. Basic Vehicle Characteristics

The basic concept is one of distributing traction power equipment over multiple cars in a fixed train set. This arrangement can vary from as few as two vehicles (married pair) to some practical length, in the range of eight vehicles. At this point, some of the advantage is lost, and it is more practical to build longer train sets from shorter fixed units. The baseline Caltrain design would be a four-car fixed unit with a cab at each end as shown in Figure 15. Since eight-car trains are required for peak service, two four-car sets would be coupled together. Caltrain currently operates with two conductors onboard every train. In this scenario, each conductor would be assigned to a four-car unit.

Figure 15 - Caltrain EMU Four-Car Train

As the previous figures indicate, passengers board at the low level, which is typically between 21 and 25 inches above top-of-rail. Basic dimensional data are provided in Table 3. This is based on the current Siemens and Alstom designs. Data for the new Bombardier EMUs are not yet available. Final dimensions of the Caltrain equipment may vary.

Nominally 50 percent of the axles would be powered. Based on the current designs, the power distribution could be either all axles powered on the two cab cars, or one truck powered per vehicle. The low-floor design, providing multi-level accommodations, requires equipment placement on the roof over the intermediate end levels of each body, as shown in Figure 16 for the Alstom Coradia. This moves much of the large electrical equipment out from under the vehicle or in the passenger space.

Table 3 - Multi-Level EMU Dimensional Data

Parameter	Alstom Coradia	Siemens Desiro
UIC Loading Gauge	UIC 505-1 Annex D	UIC 505-1 Annex D
Overall Width	9.2 feet	9.1 feet
Overall Height	15.0 feet	15.1 feet
Cab Car Length	89.7 feet	82.0 feet
Cab Car Empty Weight	144,344 pounds	132,000 pounds*
Intermediate Car Length	86.6 feet	82.0 feet
Intermediate Car Empty Weight	141,942 pounds	108,000 pounds*
Eight Car Train Length	705.2 feet	656.0 feet
Eight Car Train Empty Weight	1,145,144 pounds	1,145,144 pounds
Eight Car Train Seats	800 – 900*	750 – 800*
Eight Car Train Crush Weight	1,442,144 pounds*	1,267,200 pounds
Eight Car Train Maximum Tractive Effort	800 kW/car	800 kW/car
Maximum Axle Load	49,500 pounds	44,000 pounds
Maximum Design Speed	87 mph (124 mph Sweden)	87 mph

* Estimated

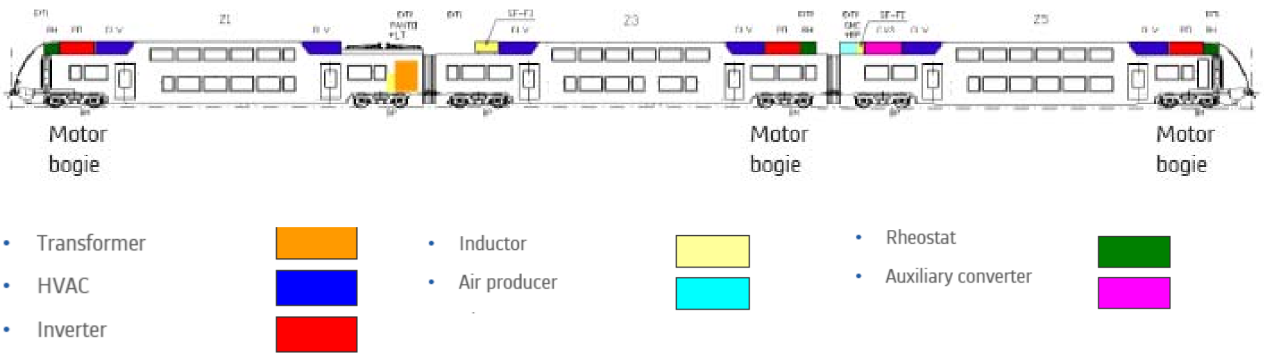


Figure 16 - Alstom Coradia Equipment Distribution

The equipment layout allows passengers to sit directly behind the cab. The inverter prevents the rear end of the cab car from being used for seating. The intermediate cars have seats at both extreme ends. In all cars, the majority of the seating is provided on the upper and lower levels between the trucks. The vestibules just inboard of the trucks would only be occupied by standees. Figure 17 shows the seating and cab layout, indicating the occupied spaces for the Coradia cab car. As currently designed, these vehicles do not comply with the Americans with Disabilities Act (ADA). European accessibility requirements are somewhat different. However, full ADA compliance will be specified for Caltrain.

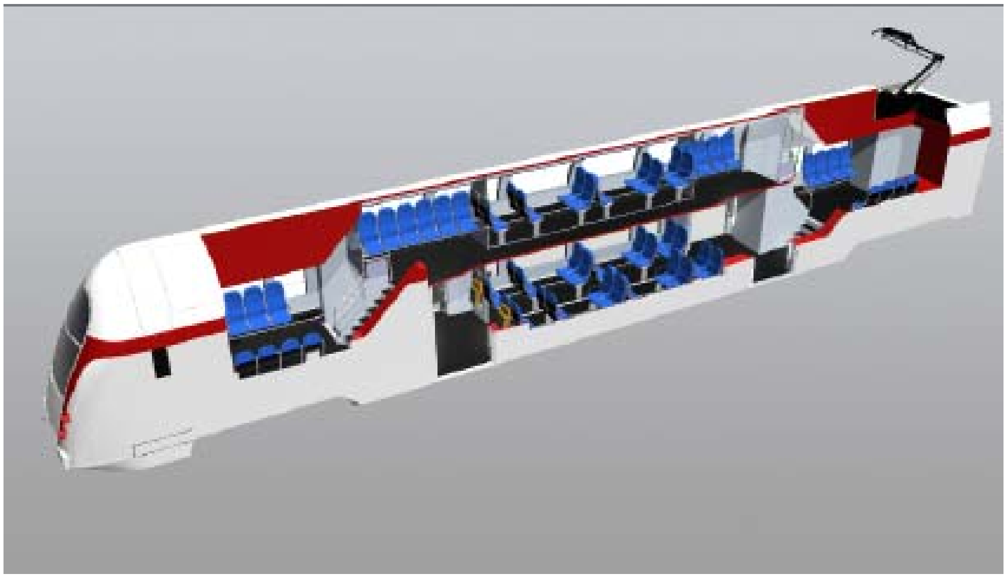


Figure 17 - Alstom Coradia Occupied Spaces

The Siemens Desiro uses a different approach with less roof-mounted equipment. This tends to limit occupied areas to the middle of the cab car, but the intermediate cars have seats distributed in a manner similar to the Coradia, as shown in Figure 18.

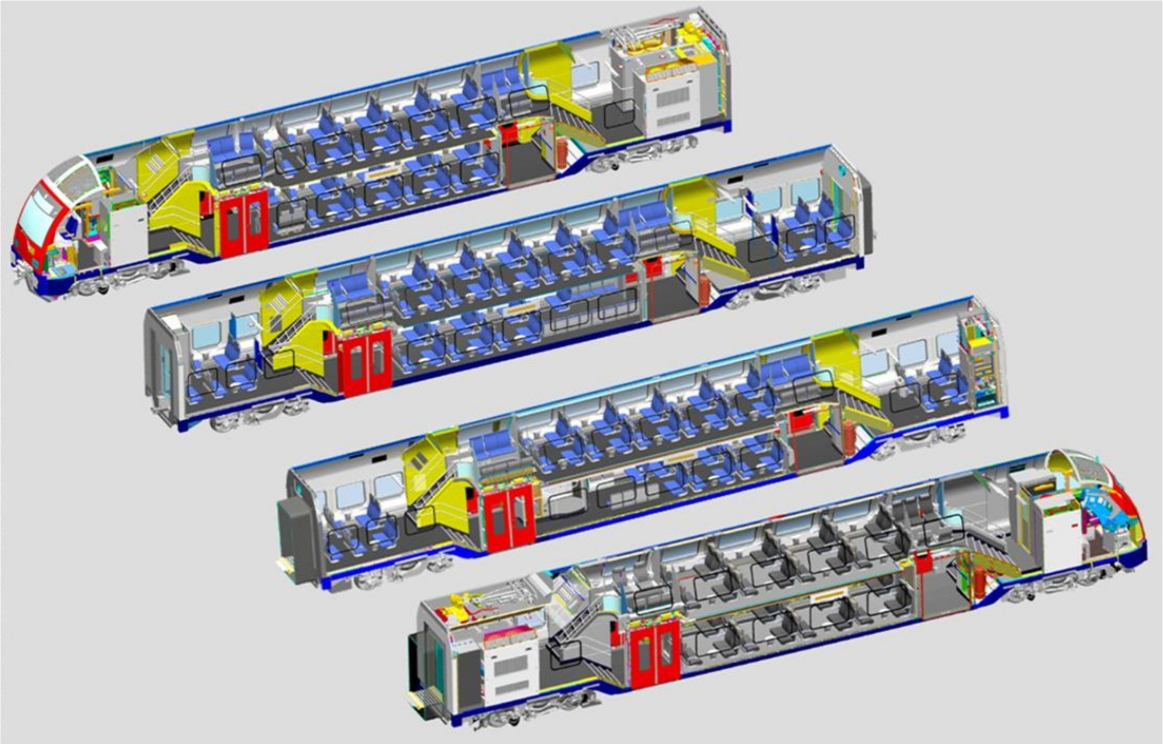


Figure 18 - Siemens Desiro Occupied Spaces

Carbodies are typically fabricated from carbon steel. Figure 19 shows a Siemens Desiro under construction.

Figure 19 - Siemens Desiro Under Construction

4. Design Standards

4.1. U.S. Design Standards

As stated earlier, the vehicles in the Caltrain fleet met all federal structural requirements when produced, but the regulations have evolved in an attempt to improve safety. The latest gallery cars, all bi-level cars, and the MP36 locomotives meet the latest regulations. The older gallery cars and F40 locomotives do not, but do meet the 800,000 pound buff strength requirement and are equipped with end-of-car structures that represented best practices at the time of construction. This section does not attempt to summarize all applicable federal regulations. Rather, it provides a brief overview of the regulations that address crashworthiness.

Federal requirements for rail vehicle crashworthiness are defined in Title 49 Code of Federal Regulations Part 238 (49 CFR 238), Passenger Equipment Safety Standards. There is currently no Federal requirement for energy absorption for Tier I equipment, with the exception of a recently released requirement for cab collision and corner posts. All requirements are given in terms of strength (except for the side structure). Tier II equipment (speed > 125 mph) has energy absorption requirements (e.g. 8 MJ for the lead power car). Table 4 provides a summary of the applicable crashworthiness requirements from 49 CFR 238.

APTA SS-C&S-034-99, Rev. 2 Standard for the Design and Construction of Passenger Railroad Rolling Stock [REF 6] augments 49 CFR 238, but for the most part matches 49 CFR 238. It adds additional requirements for corner posts, cab buffer beam strength, and seat impact performance. While it is not mandatory that S-034 be followed during the design process, passenger cars currently under design in the United States typically comply with S-034. It is Caltrain’s intent to specify APTA compliance where practicable. However, end-of-car standards above and beyond those specified in 49 CFR 238 (and/or discussed as candidates for waiver) will not be met due to the EMU CEM design. Caltrain intends to specify APTA-compliant seats in an effort to provide additional crashworthiness.

Table 4 - 49 CFR 238 Crashworthiness Requirements

Component	Description	Requirement
Static end strength	Buff strength; load applied on the line of draft (at the ends of the occupied volume)	800,000 lbf (3560 kN); no yielding
Anticlimbing mechanism	Some element at the ends of the car, e.g. coupler, coupler carrier, end beam	100,000 lbf (445 kN) up or down; no failure
Collision posts – cab end	Two full height posts located at the one-third points laterally at the end of the car	• 500,000 lbf (2224 kN) at the top of the underframe; no failure* • 200,000 lbf (890 kN) at a height of 30 inches above the floor; no failure* • *Alternate means of compliance via specific rigid body impact testing is anticipated in the near future*
Collision posts – non-cab end	Two full height posts located at the one-third points laterally at the end of the car	• 300,000 lbf (2224 kN) at the top of the underframe and, if reinforcement is used to achieve the strength, to a height of 30 inches above the underframe; no failure
Corner posts	Two corner posts located at the end of the occupied volume	• 150,000 lbf (667 kN) at the top of the underframe; no failure • 30,000 lbf (133 kN) at 18 inches above the floor; no yielding • 20,000 lbf (89 kN) at the connection to the roof; no failure • Load applied anywhere between longitudinal inward to transverse inward
Car shell	Rollover strength	• Side sill, cant rail, and (bi-level) the mid floor longitudinal must support the car on its side; max. stress less than 0.5x (yield and buckling stress) • Roof must support the car upside down; max. stress less than 0.5x (yield and buckling stress) [some deformation allowed]
Side structure	Includes side posts	• Section moduli must be greater than certain values
Truck-to-car body connection	Center pin or side connections	• 2g vertical load or 250,000 lbf (1112 kN) in any horizontal direction; no failure.

4.2. European Design Standards

The candidate Caltrain EMUs are designed to meet the structural requirements of EN12663, and the crashworthiness requirements of EN15227. For EN12663, the trainset is classified PII, as a fixed unit (semi-permanently coupled). A summary of the design loads follows:

Compressive and Tensile End Loading

- 1,500 kN (337,200 lbs) compressive at line of draft
- 500 kN (122,400 lbs) compressive diagonally at line of draft
- 1,000 kN (224,800 lbs) tensile at line of draft
- 400 kN (189,900 lbs) compressive at 150 mm (5.9 in) above structural floor*
- 300 kN (67,400 lbs) distributed across driver's window sill*
- 300 kN (67,400 lbs) at the level of the cant rail*

* Not pure compressive load due to asymmetry of load application and reaction points

Vertical Loading

- Normal operation - 1.3 x maximum passenger loading
- Lifting one end of the vehicle – 1.1 x empty weight including one truck
- Lifting entire vehicle – 1.1 x empty weight including both trucks
- Lifting in a twist -- 1.1 x empty weight including both trucks (twist dimensions undefined)

Combined Loading

- 1,500 kN (337,200 lbs) compressive at line of draft plus vertical load of 1.3 x max passenger load
- 1,500 kN (337,200 lbs) compressive at line of draft plus vertical load of 1.3 x empty weight
- 1,000 kN (224,800 lbs) tensile at line of draft plus vertical load of 1.3 x max passenger load
- 1,000 kN (224,800 lbs) tensile at line of draft plus vertical load of 1.3 x empty weight

Equipment Connections

- 3 g longitudinal acceleration acting on the mass of the equipment
- 1 g lateral acceleration acting on the mass of the equipment
- 2 g vertical acceleration acting on the mass of the equipment (1.5 g at car center)

Additional Load Cases

- Fatigue
- Track Induced Loading
- Aerodynamic Loading
- Traction and Braking Induced Loading

EN15227 provides four specific impact scenarios that must be analyzed, with the intent that a certain degree of crash energy management (CEM) be implemented to absorb impact energy in a controlled way. The classification for this equipment is CI. The scenarios are:

- A front end impact between two identical train units
  - Two 8-car trains at a closing speed of 36 km/hr (22.5 mph)
- A front end impact with a different type of railway vehicle
  - 80 tonne (176,000 lbs) freight car at a closing speed of 36 km/hr (22.5 mph)
- Train unit front end impact with a large road vehicle on a level crossing
  - 15 tonne (33,000 lb) deformable truck body at a closing speed of 110 km/hr (69 mph)
- Train unit impact into low obstacle (e.g. car on a level crossing, animal, rubbish)
  - Specific longitudinal and lateral static forces apply based on maximum operating speed

The performance criteria are, in general, as follow:

- Reduce the risk of overriding
  - One wheel set in each bogie must maintain contact with rails
- Absorb collision energy in a controlled manner
- Maintain survival space and structural integrity of the occupied areas
  - No more than 50 mm (2 inches) crush in 5 m (16.4 feet) in passenger-occupied area
  - Must provide 300 mm (11.8 inches) in front of operator’s seat in cab
- Limit the deceleration
  - 5 g maximum longitudinal acceleration in train-to-train impacts
  - 7.5 g maximum longitudinal acceleration in train-to-truck impact
- Reduce the risk of derailment and limit the consequences of hitting a track obstruction
  - Obstacle deflector must sweep debris away from wheels and
  - withstand 240 kN (54,000 lbs) longitudinal load at center line and
  - withstand 200 kN (45,000 pounds) longitudinal load at edge (30” off of center)

4.3. Design for Crashworthiness

While the Code of Federal Regulations makes allowances for alternative designs, the basic requirement for the cab-end of a vehicle yields a design with substantial corner posts, collision posts, a thick end sheet, and an underframe that can withstand 800,000 pounds applied in the line of draft without permanent deformation, as shown in Figure 20.

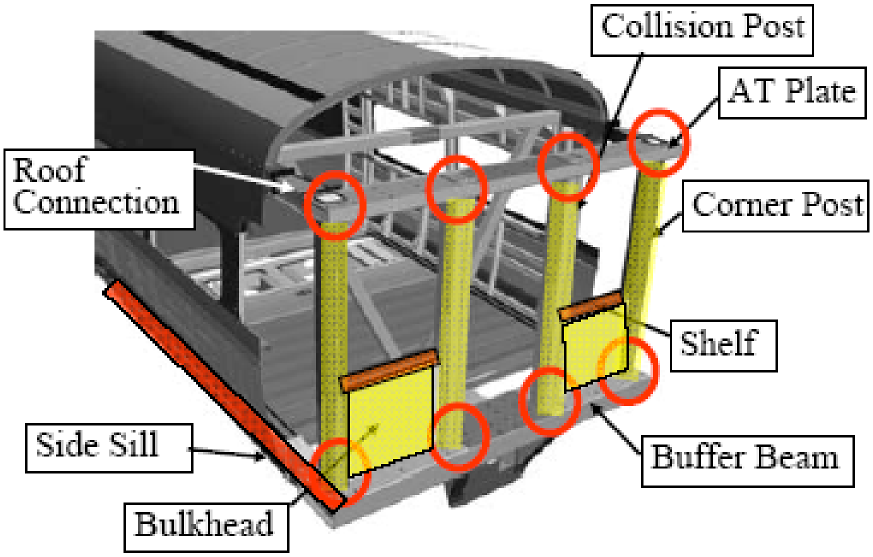


Figure 20 - FRA-Compliant Cab End and Underframe (Volpe Center)

European crashworthiness requirements yield designs that are less rigid than North American designs, relying on crash energy management (CEM) features to augment the crashworthiness of the rigid passenger compartment. A typical EMU body would fail to resist a buff load around 1.3 million pounds, compared to a compliant car body that would fail around 2 million pounds. Figure 21 shows the typical crush zones for the first two cars in a trainset. The cab is equipped to absorb more energy than each intermediate interface. The benefit of controlled crush must be balanced with the need to minimize secondary impact velocities (SIV's) of passengers in a collision.

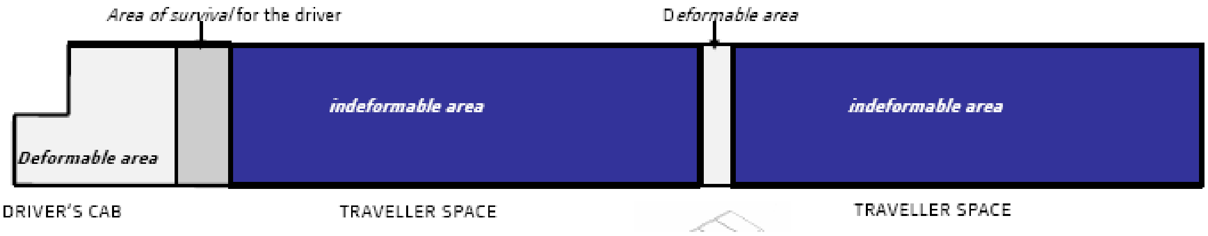


Figure 21 - Typical Crush Zones for European EMU Trainset (Courtesy Alstom)

Even though, the primary location for energy absorption is in front of the cab. It is critical that a survivable space be preserved for the operator. A typical cab arrangement is provided in Figure 22. Energy absorbing structures are in front of the operator's seat.

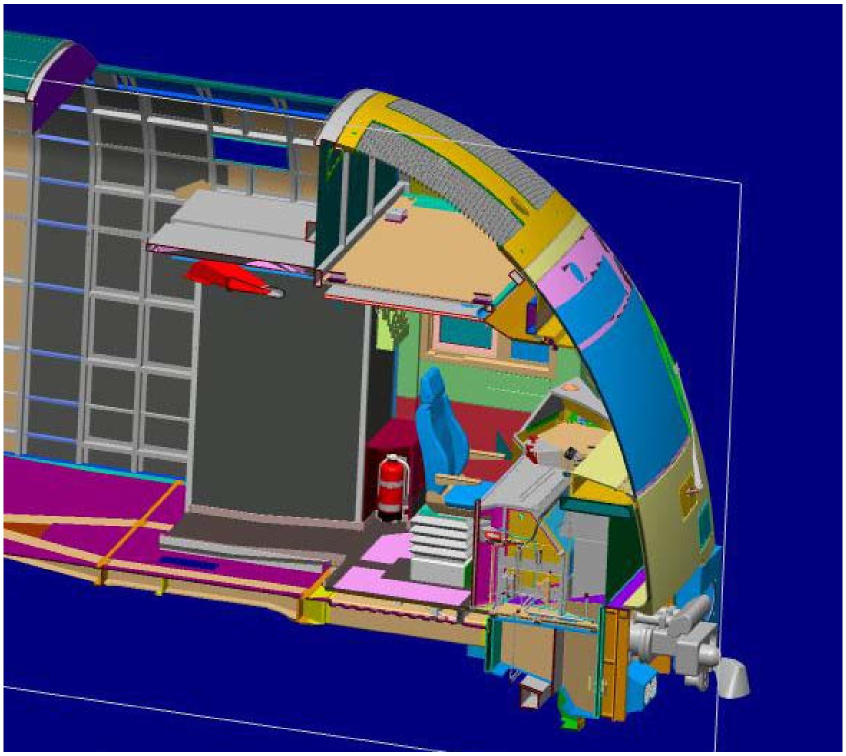


Figure 22 - Cab Showing Crush Zone in front of Operator's Seat (Courtesy Siemens)

Stripping away the sleek fiberglass front end of these vehicles, one can see the energy absorbing structures. These are typically bolt-on elements that can be replaced following a collision, without major cutting and welding. Figure 23 shows cab energy absorbers for the Alstom cab. Figure 24 shows the Siemens cab.

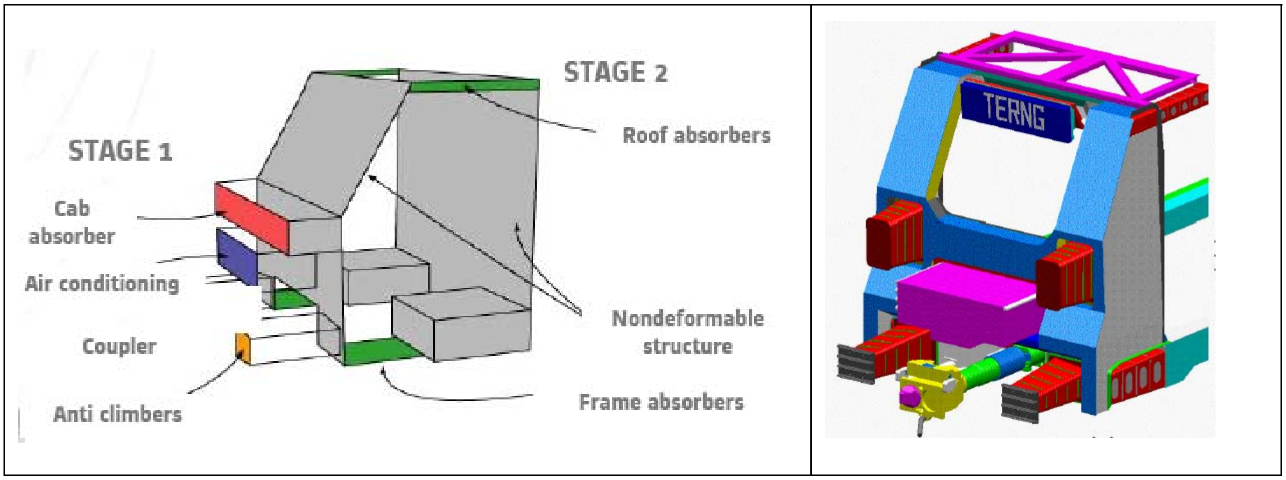


Figure 23 - Typical Cab Energy Absorber Arrangement (Courtesy Alstom)

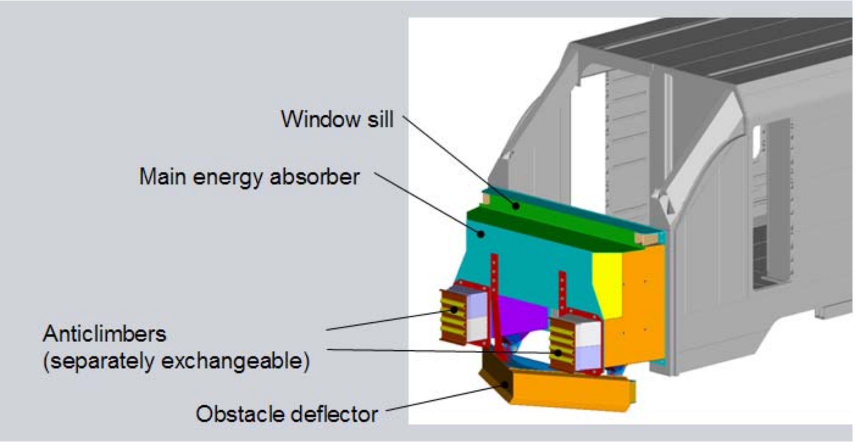


Figure 24 - Typical Cab Energy Absorber Arrangement (Courtesy Siemens)

A key element in obtaining full engagement of the energy absorbing structures is the push-back coupler. Under a high load, the coupler is allowed to push back into a pocket in the underframe. This clears the way for engagement of the absorbers, maintains the opportunity for couplers to stay connected, and dissipates additional energy as the push back mechanism is designed to absorb energy through permanent deformation of the pocket.

While the deformable elements look simple, they require a high level of design to ensure predictable performance. This design work is validated through individual component testing, and even full scale testing as shown in Figure 25.

Figure 25 - Typical Cab Energy Absorber Test Results (Courtesy Alstom)

The second location for energy absorption is at the interface between each carbody. These bodies are connected by a drawbar with pushback mechanisms, which helps prevent telescoping in a derailment by first absorbing energy in a controlled manner, then by allowing anticlimbers to make contact, preventing override. Energy is absorbed first by the push back mechanism, then through crush zones in the interface, as shown schematically in Figure 26. Note the absorbers with ribs for added anticlimbing capability and the drawbar with absorbers at the ends where pushback occurs. Figure 27 depicts actual components and energy absorption levels.

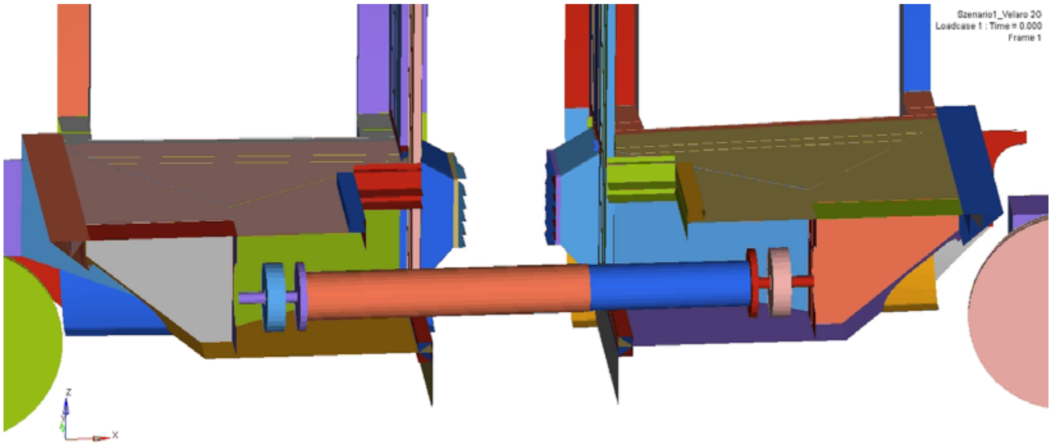


Figure 26 - Intermediate Connection Energy Absorbers (Courtesy Siemens)

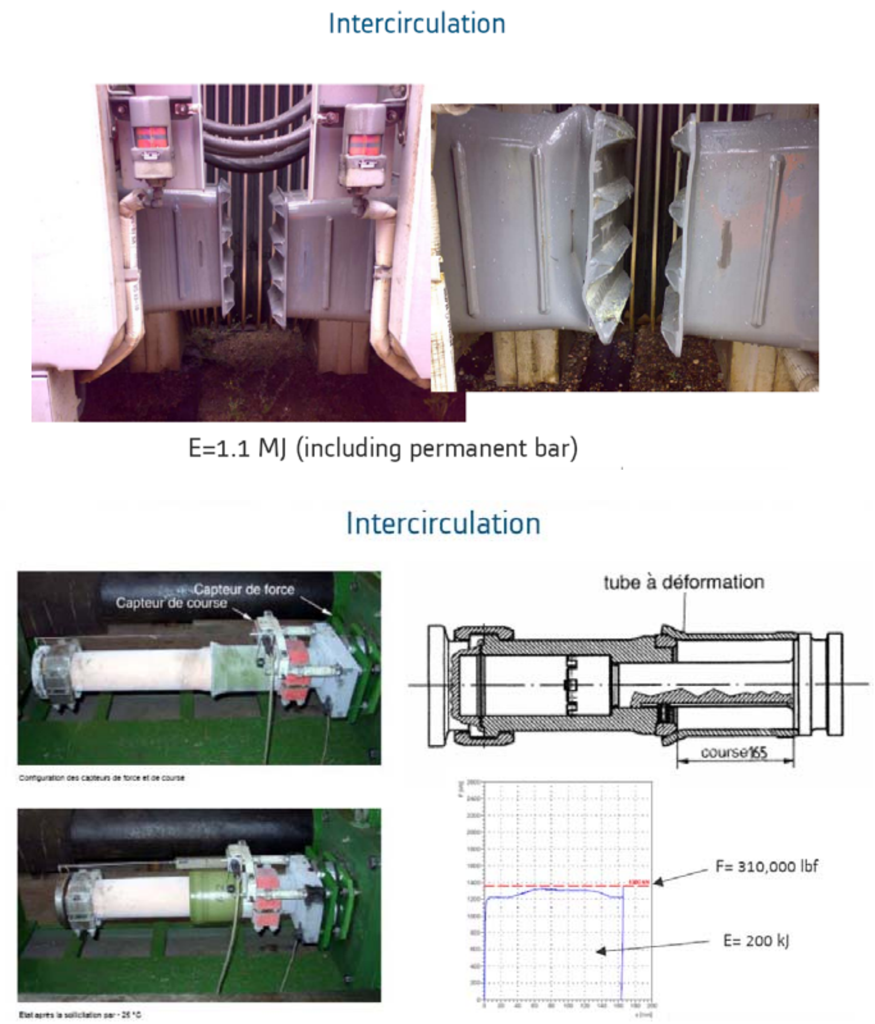


Figure 27 - Intermediate Connection Energy Absorbers (Courtesy Alstom)

5. Analyses Performed on Proposed Equipment

This section provides descriptions of several analyses that have been conducted to investigate and demonstrate the crashworthiness of the European EMUs under consideration for the Caltrain system. In some cases, the analyses are directed toward specific U.S. regulations or APTA requirements. In other cases, analyses are directed toward specific scenarios identified by the Hazard Analysis as discussed in Section 6 of this report. Further analyses are supplemental and descriptions are provided here to indicate the scope of work that has been undertaken by the Caltrain team to ensure that collision safety will not be compromised by utilizing European EMUs designed to EN15227 and EN12663 supplemented by specific Caltrain specifications.

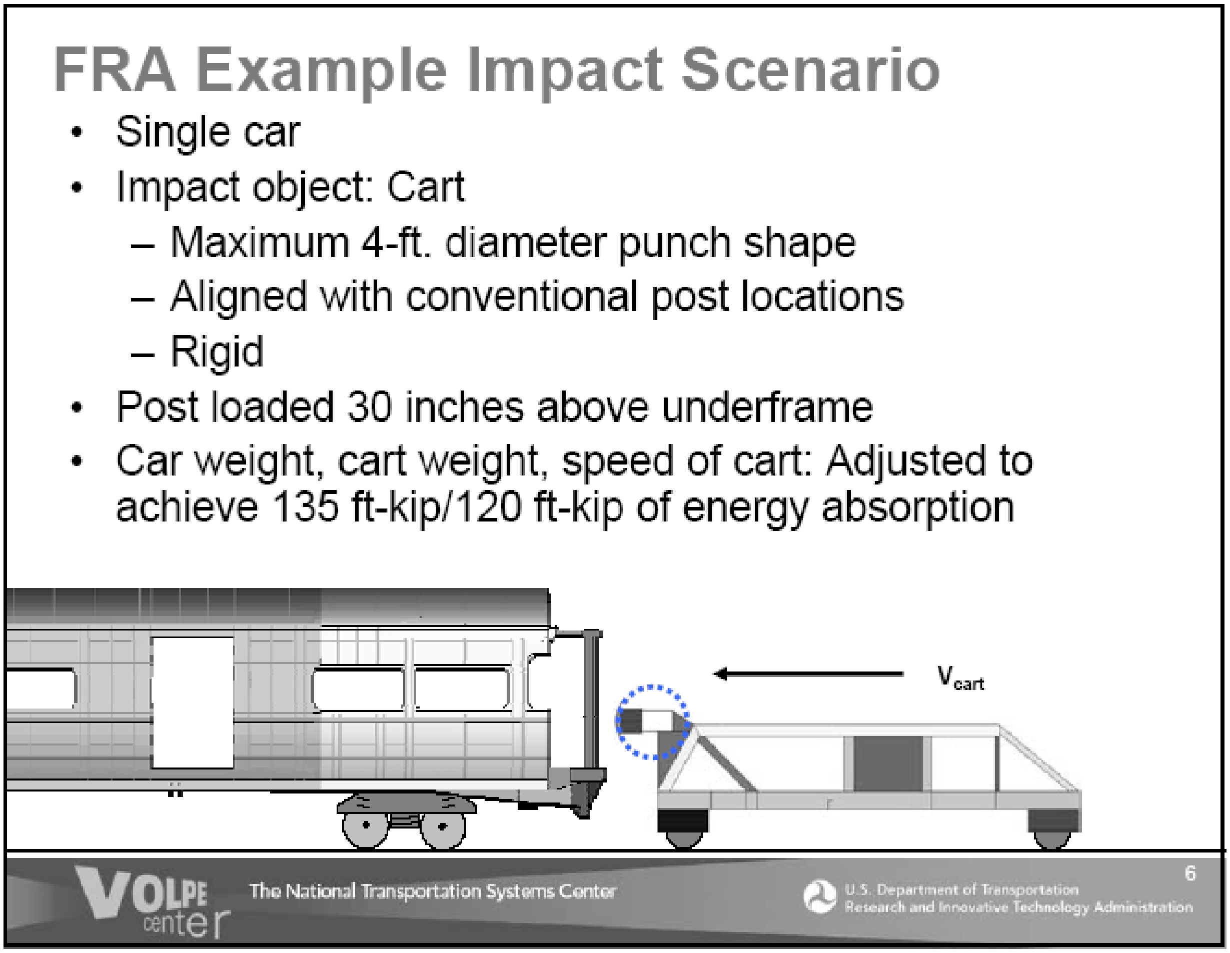
The analyses presented in this report fall into three mishap categories:

- Grade crossing collisions
    - Impact with a 10,000 pound steel coil per anticipated revisions to 49 CFR 238 (show compliance with anticipated revised FRA regulation and/or show protection is not compromised)
    - Impact with a 33,100 pound deformable object (highway trailer) per EN15227 (demonstrate current state of the art in European design and offer comparison with FRA-compliant equipment)
    - Impact with an automobile (provide outcome data for hazard analysis)
    - Impact with a tractor/trailer other than prescribed by EN15227 (show other analyses done by carbuilders and provide outcome data for hazard analysis)
- Train-to-train collisions
    - EMU trainset impacting the locomotive end of a standing compliant trainset (demonstrate performance consistent with intent of 49 CFR 238.203 and provide outcome data for hazard analysis)
    - Compliant trainset with cab car leading impacting the locomotive end of a standing compliant trainset (provide comparative data for compliant equipment and provide outcome data for hazard analysis)
    - EMU trainset impacting a standing EMU train set (current state of the art in European design and provide outcome data for hazard analysis)
- Post-derailment impacts
    - EMU trainset impacting a flat wall (provide outcome data for hazard analysis)

- Compliant trainset with cab car leading impacting a flat wall (provide outcome data for hazard analysis)

5.1. Steel Coil Impact Analysis

The current practice in the U.S. (relevant to the Caltrain project) is to provide protection in grade crossing collisions by specifying the strength and energy absorption capability of the cab car end frame. A new Federal regulation (not yet enacted at the time of this writing) permits demonstration of end frame crashworthiness by simulating an impact between a ram, mounted on a moving car, and the cab car end frame at particular locations without causing complete separation or excessive deformation of the posts. Figure 28 shows an illustration of this collision. This is equivalent to the cab car impacting a rigid coil, and both Siemens and Alstom have conducted three-dimensional finite element calculations for this latter case on the types of EMU's being considered for the Caltrain system. This represents the main demonstration that the EMU's possess the necessary grade crossing crashworthiness and the results of those calculations are summarized in this section. The final vehicle procurement specification will be written to require analysis for the ram impact.



FRA Example Impact Scenario

- Single car
- Impact object: Cart
  - Maximum 4-ft. diameter punch shape
  - Aligned with conventional post locations
  - Rigid
- Post loaded 30 inches above underframe
- Car weight, cart weight, speed of cart: Adjusted to achieve 135 ft-kip/120 ft-kip of energy absorption

Figure 28 - FRA Proposed End Frame Energy Absorption Analysis/Test (from Volpe)

The final rule that the FRA is preparing to release permits analysis of the ram impact shown in Figure 28, but when the rule was released as a notice of proposed rulemaking, the requirement was to withstand an impact with a steel coil. Figure 29 shows a photograph of a test setup that corresponds to the conditions in the original NPRM.

Figure 29 - Steel Coil Impact Test Setup

Specific requirements in that version of the NPRM were as follows:

- Proxy object (essentially a steel coil) mass = 10,000 lb (4530 kg); diameter 48 inches; depth 36 inches; simulated as rigid.
- Impact velocity:
    - Collision post impact: 21 mph (33.6 km/hr)
    - Corner post impact: 20 mph (32 km/hr)
- Required Performance and Energy Absorption:
    - Collision post impact centered at 30 inches above the top of the underframe
    - Corner post impact centered at 30 inches above the top of the underframe
    - Both result in less than 10 inches (254 mm) of deformation; no complete fracture.
    - Posts cannot completely separate from car.

Both Alstom and Siemens conducted three-dimensional finite element analysis for the coil impact case using existing vehicles that represent the end structure that would be offered to Caltrain. In both cases, the rail car is held fixed, impacted by the rigid coil moving at the appropriate velocity.

Figure 30 shows three time steps of the Alstom collision post analysis; the last frame corresponds to the point of maximum crush. Figure 30 provides a summary of the load-crush response for this case. [Ref 7]

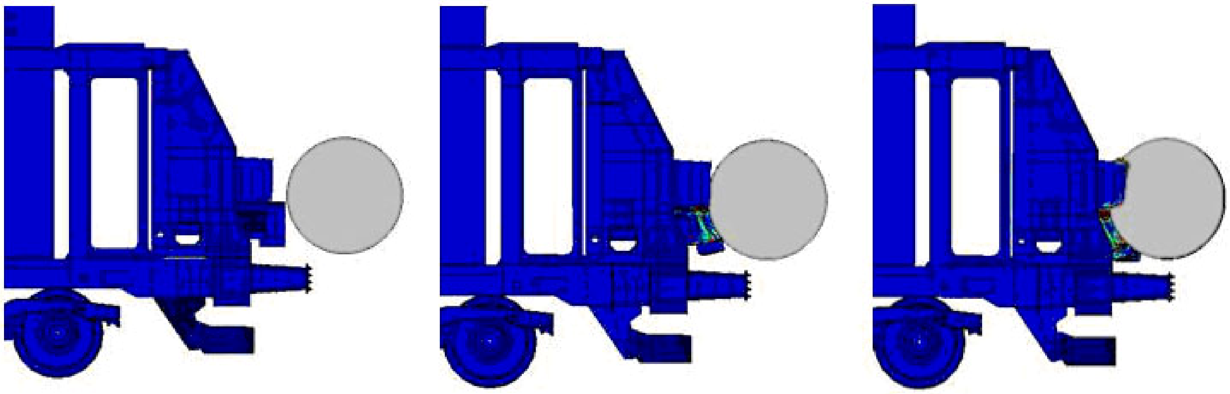
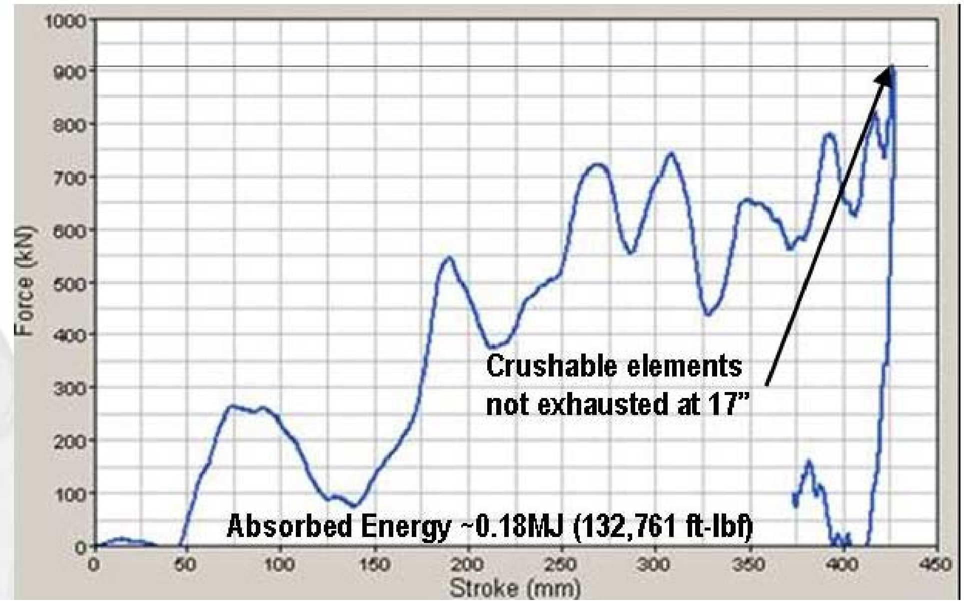


Figure 30 - Alstom Collision Post Steel Coil Impact Results



Crushable elements not exhausted at 17”

Absorbed Energy ~0.18MJ (132,761 ft-lbf)

Figure 31 - Alstom Collision Post Steel Coil Impact Crush Curve

The following is applicable to all of the collision and corner post analyses conducted by Alstom and Siemens:

- Force in the rail car is reacted by constraints at rear of the car.
- Stroke is calculated as the change in distance between the coil and the rear of the car. (longitudinal direction)
- All components remain intact (no fracture).

- Impact energy is absorbed by crush zone elements.
- There is no intrusion into the cab operator compartment. (CFR NPRM allows 10 inches)

Corner post impact analysis results were also provided and showed that the requirements of the original NPRM are satisfied. Figure 32 shows the corner post area crush for the Alstom cab. Figure 33 shows the Siemens car in the corner post impact case. [Ref 8]

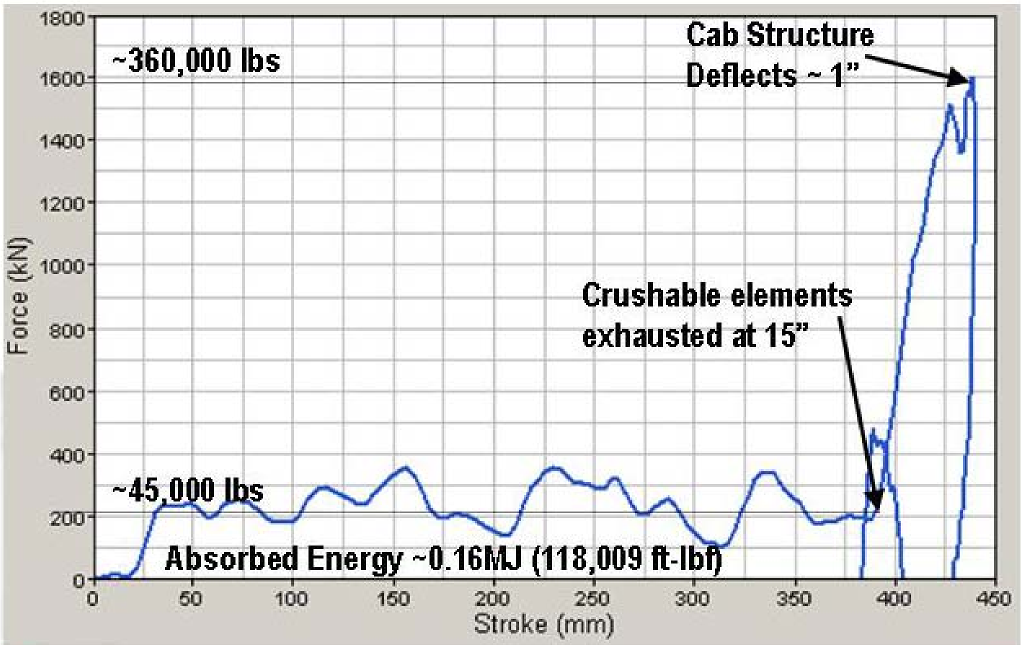


Figure 32 - Alstom Corner Post Steel Coil Impact Results

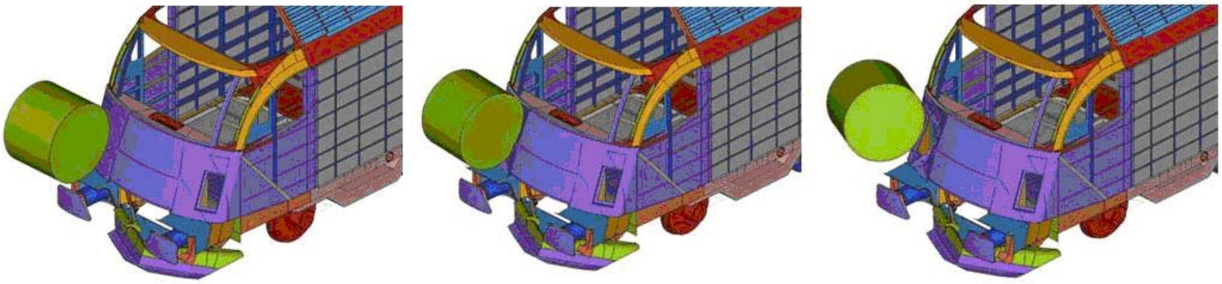


Figure 33 - Siemens Corner Post Steel Coil Impact Results

5.2. EN15227 Truck Collision Analysis

EN15227, the crashworthiness standard to which the EMUs under consideration by Caltrain were designed, includes a required collision scenario with a deformable object. This object is intended to represent a truck in a grade crossing. The object has a mass of 33,100 lb (15,000 kg) with a particular geometry and crush properties. Figure 34 shows the geometry of the object and the minimum force-displacement response for a particular impact scenario (impact with a rigid sphere.) The rail cars in question were designed to sustain an impact with this deformable object at a speed of 69 mph (110 km/hr) without excessive deformation of the occupied volume. Excessive deformation is defined as a reduction in length of passenger survival spaces more than 50 mm (2 inches) over any 5 m (16.4 ft) length or the plastic strain greater than 10 % in these areas. A specific space must also remain for the cab operator.

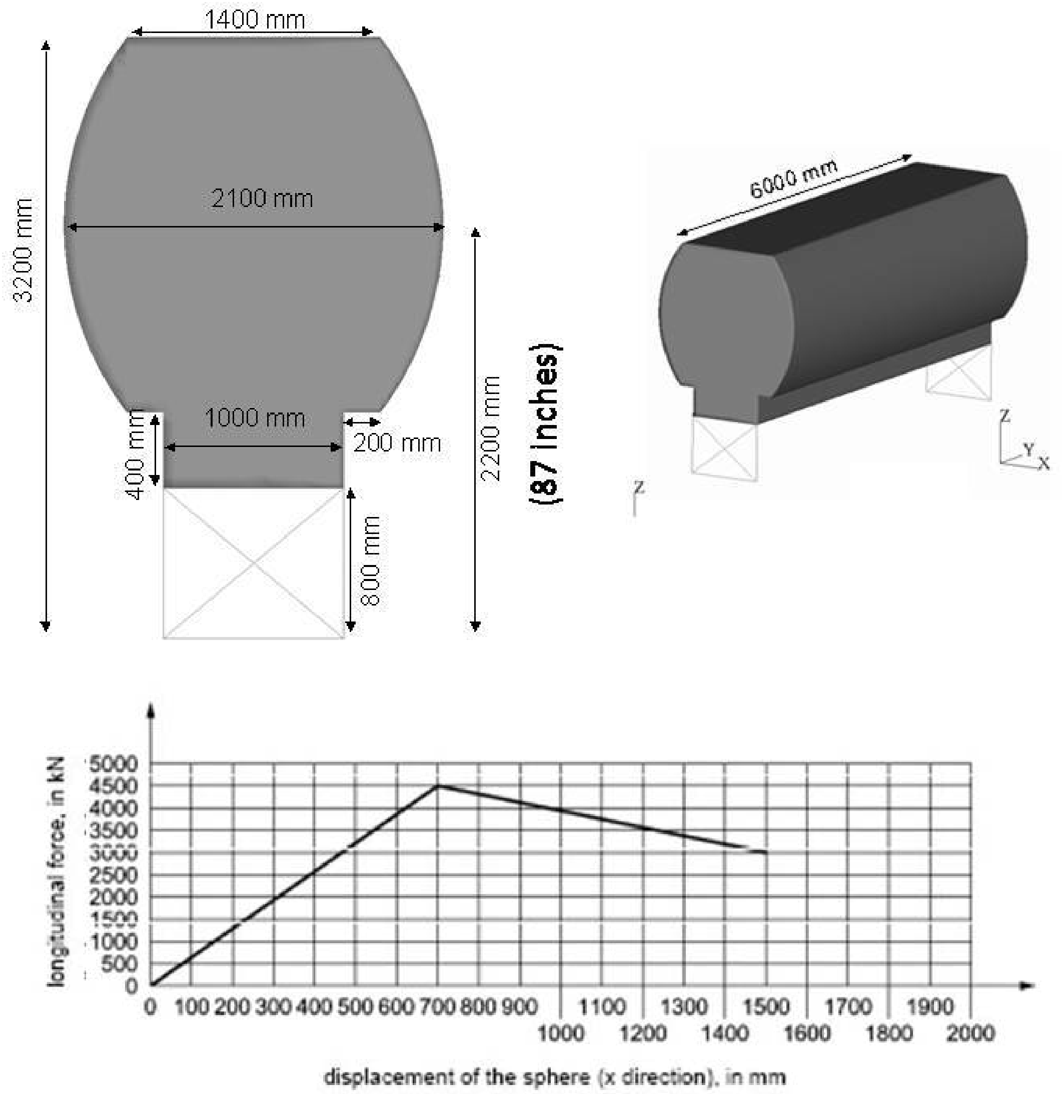


Figure 34 - Highway Truck Dimensions and Stiffness (from EN15227)

Both Alstom and Siemens have performed analyses for the deformable obstacle case of EN15227 on their vehicles, but complete reports have not yet been provided to the Caltrain team. Figures 35 and 36 show calculated deformation and Von Mises stress distributions for the Alstom cab in this scenario. [Ref 9] Large deformation and high stresses are confined to the elements designed to crush; that is, deformations and stresses in the occupied volumes are low. Deformation in the survivable space in the cab is also very low. The Alstom analysis includes their windshield retention system, which adds an additional layer of safety that is not currently mandated by EN15227 or 49 CFR 238.

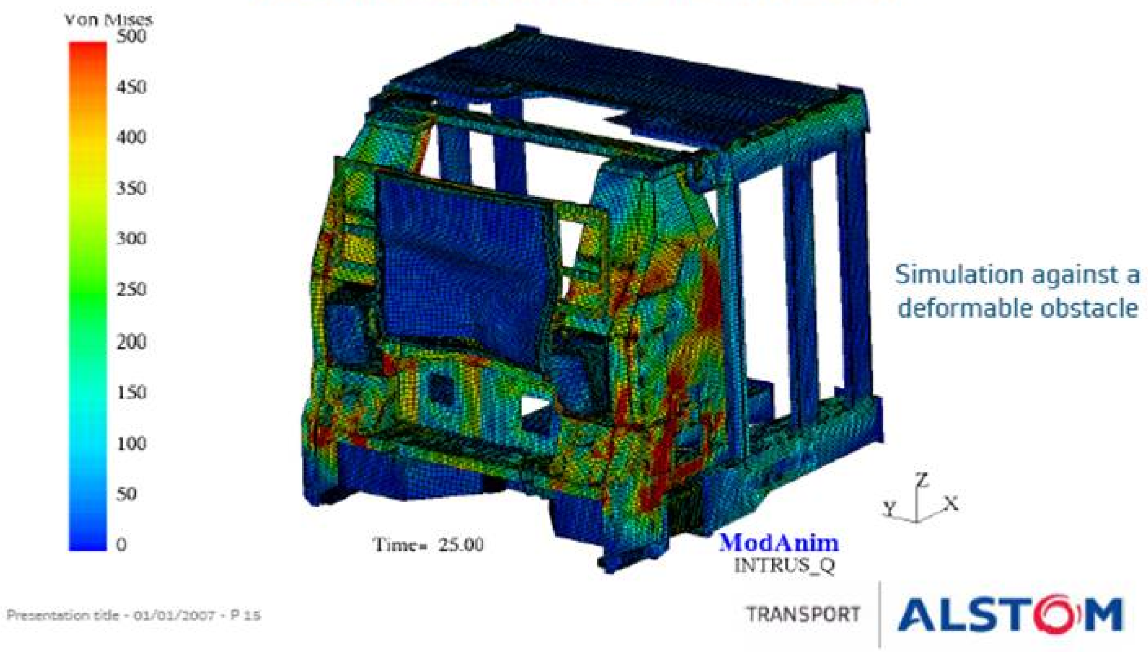


Figure 35 - Alstom EMU Cab Mises Stress – EN15227 Truck Impact (69 mph)

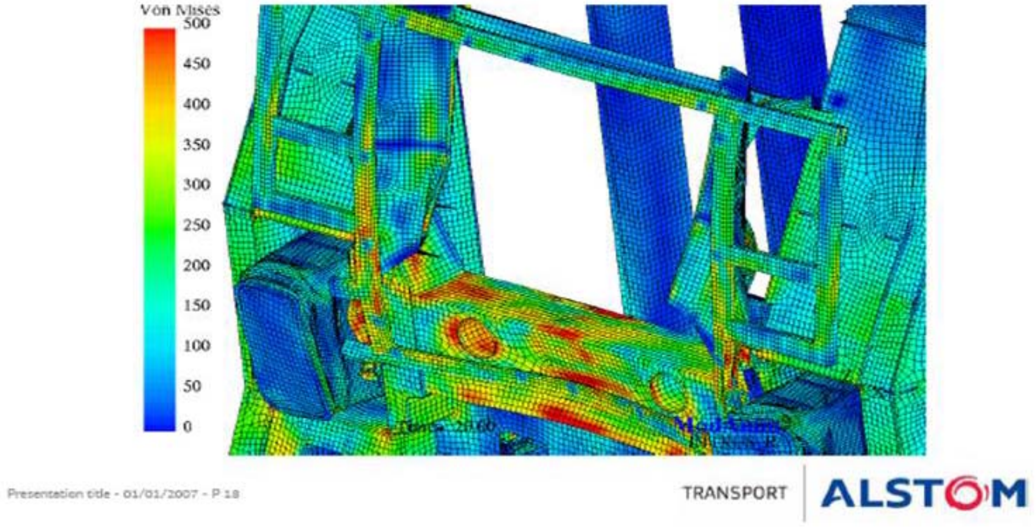


Figure 36 - Alstom EMU Cab von Mises Stress – EN15227 Truck Impact (69 mph)

Siemens also provided results for the deformable obstacle collision scenario of EN15227 with their Desiro EMU vehicle. Their simulation results are in the form of crush at each time step, creating an animation. Figure 37 provides images from three time steps that show how both the truck body and the cab energy absorbers crush. Due to the height of the truck body, it eventually rotates into the windshield of the cab, as shown previously in the Alstom analysis, causing significant crush of both bodies. However, the Siemens analyses also predict no intrusion into the occupant volume.

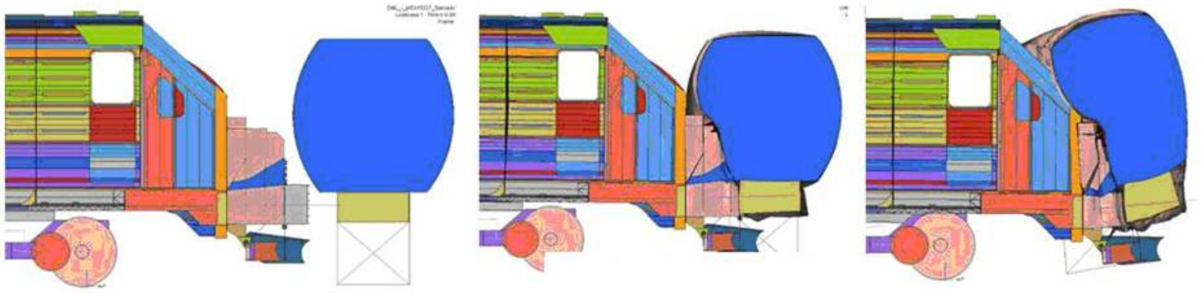


Figure 37 - Siemens EMU Cab Crush – EN15227 Truck Impact at 69 mph

5.3. FRA Compliant Cab Car -- EN15227 Truck Impact

One of the requests made by the FRA during the course of discussions on evaluating the crashworthiness of the European EMUs was to assess the crush behavior of a compliant car in the EN15227 deformable object collision scenario. In the meantime, the Volpe Center has carried out a more comprehensive calculation, but the results of the Caltrain team work are provided here for reference. Note that, at the time this request by the FRA was made, it was understood that a quick and approximate analysis was acceptable, since the Volpe Center would eventually conduct a detailed analysis.

A model for a compliant car was provided by the Volpe Center to the Caltrain team for the analysis. This model corresponds to a partial section of a single level, state-of-the-art car used in several studies. [Ref10] The model was provided in the form of an input file and was imported into Abaqus as an orphan mesh. This translation resulted in some model anomalies that caused the analysis to terminate prematurely as discussed below. Further analysis for this case was not continued, because it was still possible to draw conclusions.

The conditions for the Caltrain team analysis included the following:

- A simple extension was added to the model to increase the mass of the car to about 50,000 lb.
- Only one rail car was simulated; EN15227 requires the entire train to be simulated.
- A coupler was not included as required by EN15227.
- Impact speeds of 50 and 70 mph were used. The speed of 70 mph (112 km/hr) is close to the speed (110 km/hr) used to design the European EMUs under consideration by Caltrain.

- The rail car was given the initial speed of 50 or 70 mph, and the rear of the car was constrained to move only in the longitudinal direction.

Figure 38 shows the relative scale of the bodies and the height at which the end frame will first impact the object, which is well above the end sill.

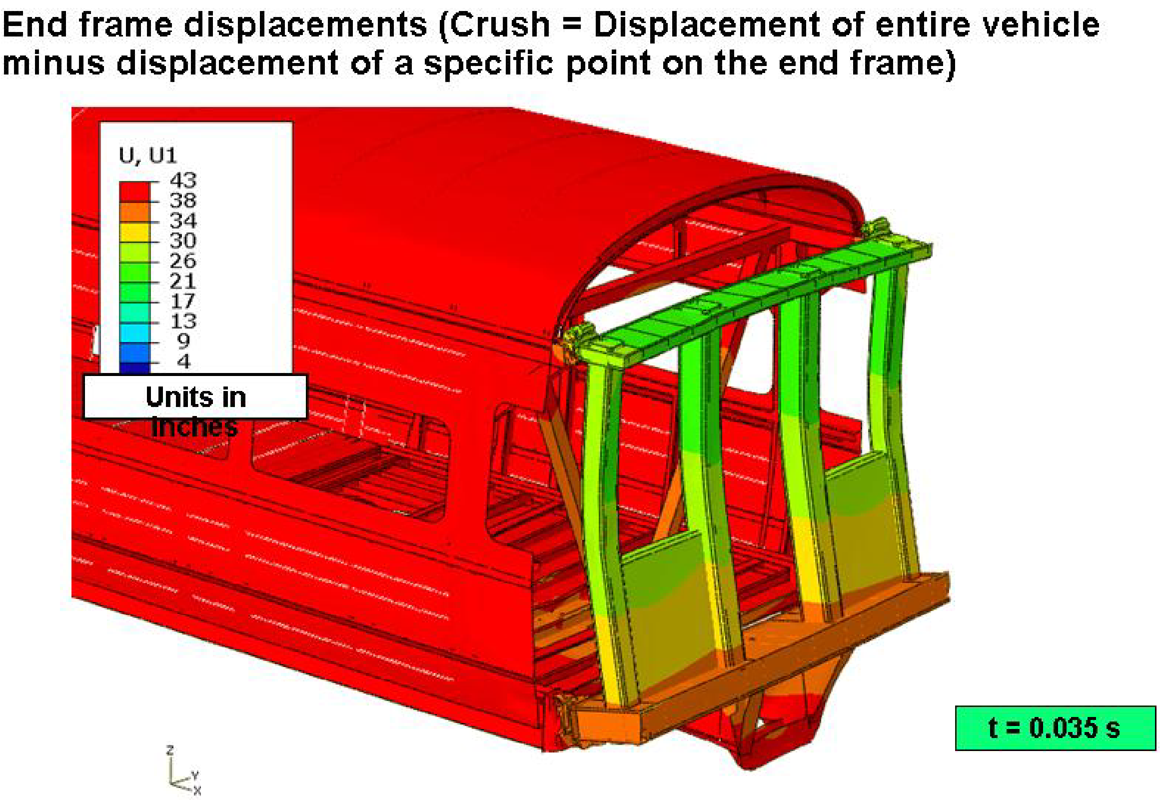
Figure 38 - Compliant Cab Car Impacting the EN15227 Truck

Table 5 lists the calculated end frame deformation obtained before the analysis terminated. This deformation corresponds to displacement of the rear of the collision post relative to a point at the side of the car just inboard of the cab operator space. The analysis terminated because of a problem with the mesh in the mid section of the car body. Refinement of the model was not pursued because of the knowledge that the Volpe Center would be carrying out calculations. [Ref 11] Analysis of the velocities of the rail car and deformable object indicated that no additional deformation would occur in the 50 mph case but that additional deformation would likely occur in the 70 mph case. Figure 39 shows an example of the calculated deflection of the end frame, in this case for the 70 mph closing speed.

Operators in most U.S. cab cars are seated close to the inside of the end frame. It is not uncommon for the seat in the operator's compartment to have about 15 to 20 inches of clear space to the inside of the end frame. EN15227 requires that 300 mm (11.8 inches) of space remain in front of the seat after collision with the deformable object (and in other scenarios). The implication is that, for the conditions simulated by the Caltrain team, the compliant car might satisfy the EN15227 requirements for the 50 mph case, but would not for the 70 mph case. It is possible that there would not be enough space for the 50 mph case if the entire train were simulated.

Table 5 - Caltrain Team Compliant End Frame – EN15227 Analysis Results

Impact speed (mph)	Simulated time at which the computer analysis fails (s)	Calculated end frame crush at this time (inches)
50	0.054	5.5
70	0.035	15



End frame displacements (Crush = Displacement of entire vehicle minus displacement of a specific point on the end frame)

Figure 39 - Caltrain Team Compliant End Frame – EN15227 Truck Impact at 69 mph

5.4. One Dimensional Analysis of Grade Crossing Collisions

One-dimensional, lumped mass collision dynamics calculations were carried out as part of the Caltrain 2025 project study to investigate general collision consequences. This section describes the calculations related to a particular grade crossing collision, but much of the methodology is applicable to the train-to-train and train-to-fixed object collision simulations described in other parts of this report.

One-dimensional analyses were conducted early in the study of the EMU crashworthiness for the Caltrain system to investigate impact with an automobile and the approach and results are described here. Two aspects are of interest: crush deformation and derailment potential.

The automobile collision analysis was carried out for impact between a 4,000 pound automobile and a four-car train. An automobile with this weight was selected as representative of a heavy, common automobile; for example, a Chevy Impala weighs about 3500 lb and a Toyota Camry weighs about 3100 lb. Although computer simulations were run for this impact case, the outcome is clear from a consideration of relative crush strengths as will be discussed below. Thus, the exact selection of rail vehicle crush responses for this case is not critical. The impact scenario is illustrated in Figure 40. A four-car EMU trainset was used in this early analysis. Configurations up to eight cars are likely to be run on the Caltrain system, but there is a negligible effect of the train mass for the case in which the impacted object has a mass small compared to the leading rail vehicle; in this case 4,000 lb compared to 160,000 lb. Most of the energy in such collisions is absorbed at the impact interface and, for the types of EMUs under consideration, by the impacted automobile.

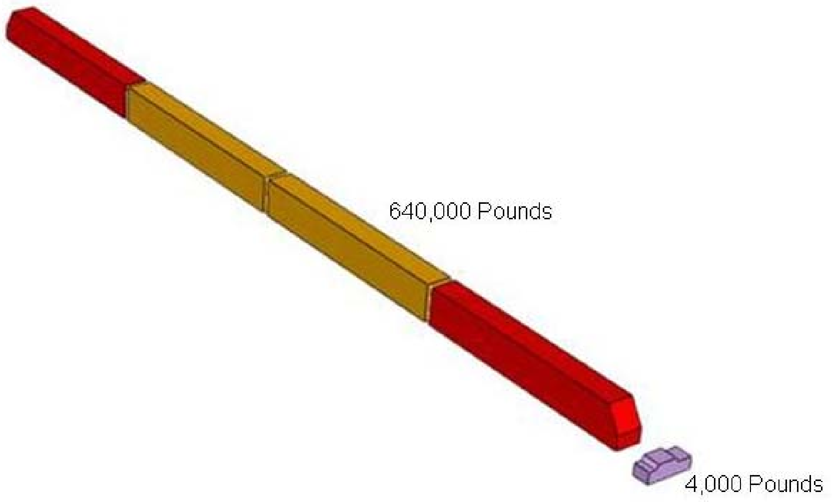
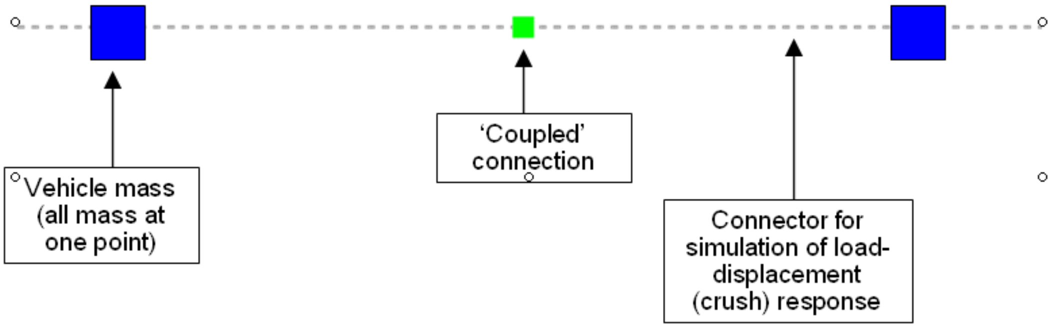


Figure 40 - One Dimensional Grade Crossing Impact Scenarios

The one-dimensional lumped-mass model shown in Figure 41 was used with the solver “Abaqus Explicit”. This model was adapted from a model used for another project and includes a braking friction of 0.1 and a draft gear response that simulates one cycle of hysteresis. However, these latter parameters have a negligible effect on the results of the analyses described here. The key inputs to the model are vehicle mass and stiffness (crush response), as well as impact speed.



- Initial speed applied to moving train
- Braking friction applied as gravity force

Figure 41 - One-Dimensional Lumped Mass Model Schematic

Figure 42 provides a summary of the crush responses used for the various vehicles. The response for the automobile is derived from *HTSA's Vehicle Compatibility Research Program* [Ref 12]. The peak crush load is taken as 100,000 lb. A decreasing load at large values of crush is meant to simulate the break-up of the automobile. The response for the compliant rail car is a very rough approximation of the crush response of a bi-level car measured by the FRA/Volpe Center and reported in *Review of a Single Car Test of Multi-Level Passenger Equipment* [Ref 13]; it captures the initial peak load but not the subsequent fluctuating load. The response for the CEM car is derived from consideration of the various EMU vehicles reviewed; it does not represent a particular vehicle model. The stepped load-crush response of the CEM car corresponds to sequential loading of the various crushable elements at its end. The actual form of this curve depends on the details of the interaction between colliding bodies. A different response will be obtained depending on the vertical location of impact. The important point here is that the crush loads for the various elements at the ends of the compliant and CEM cars are higher than that for the automobile.

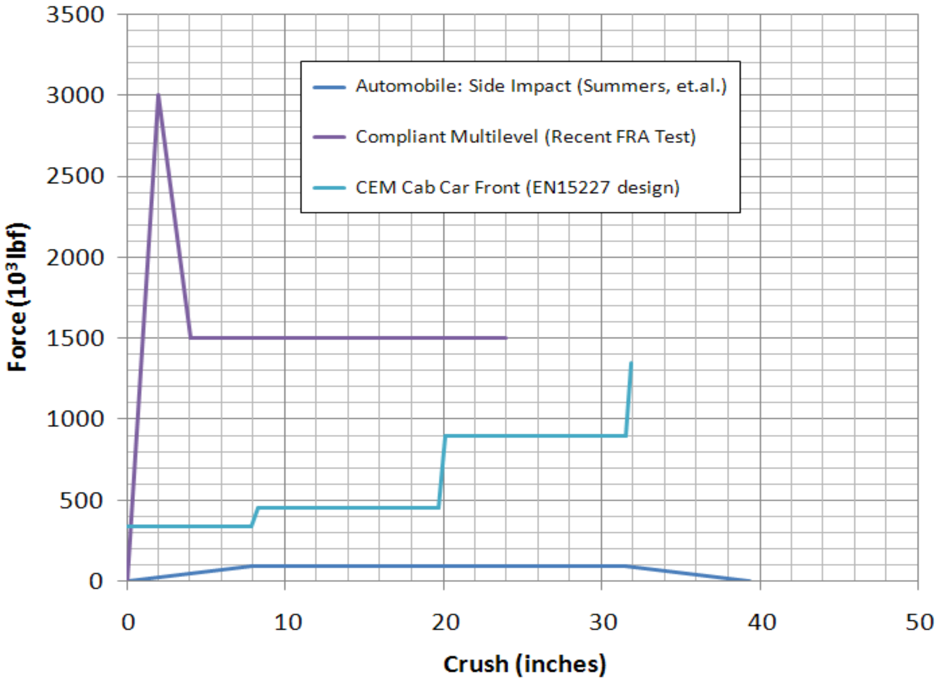


Figure 42 - Crush Characteristics of Bodies in an Auto-Train Collision

Figure 43 shows the calculated crush for the automobile and the EMU cab. There is no occupant volume crush in the EMU. Essentially all of the crush and energy absorption occurs in the impacted automobile. As stated previously, this result is obvious from consideration of the load-crush curves in Figure 42; the strength of the rail car ends is substantially greater than that of the automobile.

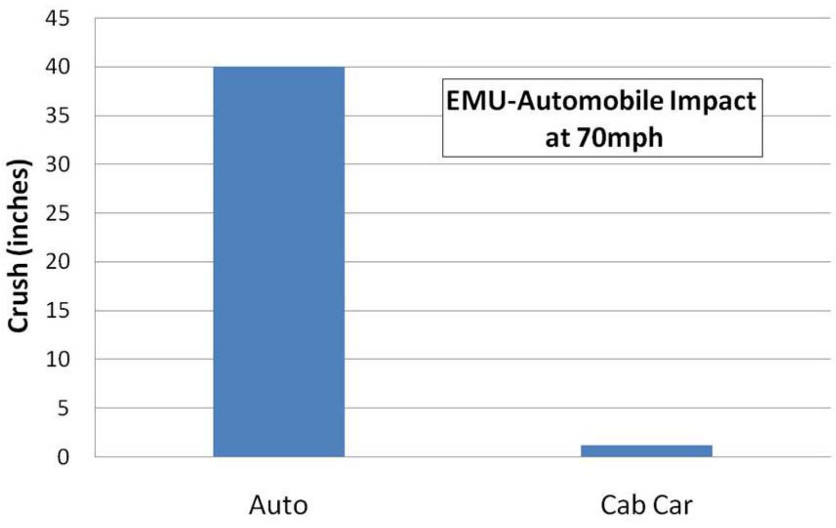


Figure 43 - Train-Automobile Collision Results at 70 mph

Another potential consequence of a grade crossing collision with an automobile is derailment. The one-dimensional collision dynamics analysis is not used to assess this mode but some commentary on this issue is offered. Current Federal regulations require a pilot on the cab car, but only geometric characteristics are specified: the bottom of the pilot must be in the range of 3-6 inches above the top of rail. APTA S-034 also does not include specific requirements for the pilot, but it is not uncommon for more stringent requirements to be included in a vehicle procurement specification. For example, the recent SCRRA specification requires the following for the pilot:

- Apply 50,000 lb longitudinally at the rail locations simultaneously
- Apply 20,000 lb longitudinally at the center
- Apply 30,000 lb transversely.

The allowable stress in these cases is the lower of the yield strength, 80% of the ultimate strength, or the critical buckling stress.

EN15227, the standard to which the European EMUs are designed, requires the following without significant plastic deformation:

- 40,000 lb (180kN) applied longitudinally to the center
- 33,700 lb (150kN) applied longitudinally 30 inches laterally from the center,

Designing the EMU pilot to the EN15227 requirements and the fact that the EMUs will have a comparable weight to compliant cars, indicates that there should be comparable resistance to derailment in grade crossing collisions.

5.5. EMU – Tank Truck Collision Analysis Performed by Alstom

Prior to the release of EN15227, Alstom performed a three-dimensional finite element analysis of a CEM equipped EMU striking a tank trailer at a crossing; the tank trailer is not the same as that now used in 15227, but is included here for additional information. [Ref 14] Two analyses were performed, one at a perpendicular angle and one with the trailer oriented 15 degrees off of perpendicular. The impact speed was 69 mph (110 km/hr). The trailer weighed approximately 66,000 pounds and the tractor weighed approximately 15,000 pounds, for a total weight of 81,000 pounds. This is consistent with US highway equipment (The truck weight limit in California is 80,000 lb.). Figure 44 shows the perpendicular impact configuration.

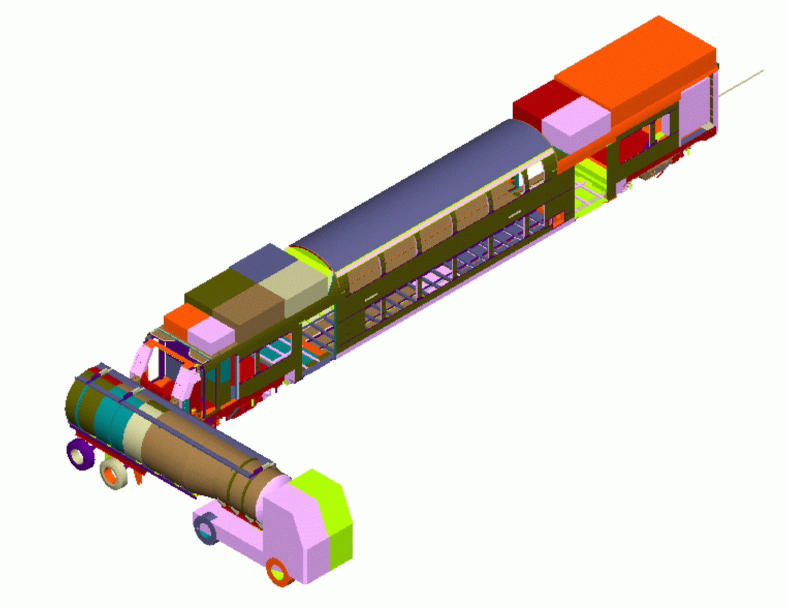


Figure 44 - Alstom 4-Car EMU Trainset Impacting an 66,000 Pound Tank Trailer

The results of these calculations are listed in Table 6. The amount of crush that the cab car can sustain before intrusion into the occupied volume occurs is about 28 inches. Thus, the integrity of the rail vehicle cab is maintained, and the deceleration of the train is low enough that secondary impact velocities would be acceptable.

Table 6 - Pre-EN15227 Tank Truck Impact Results

Parameter	Perpendicular Impact	15 Degree Impact
Kinetic Energy at Impact	141 MJ	141 MJ
Energy Absorbed by Tank Trailer	4.0 MJ	4.7 MJ
Energy Absorbed by Train	2.7 MJ	3.1 MJ
Cab Shield Deformation at Center Line	17 inches	18 inches
Maximum Deceleration of the Train	3.3 g	3.6 g

During the impact with the trailer oriented 15 degrees from perpendicular, slightly more energy was absorbed by both the trailer and the train. This is due to the increased contact between the upper pillars of the cab and the soft part of the tank. This caused more damage to an area of the cab that is not specifically designed to provide much deformation. However, the survivable space remained intact, as shown in Figures 45 and 46.

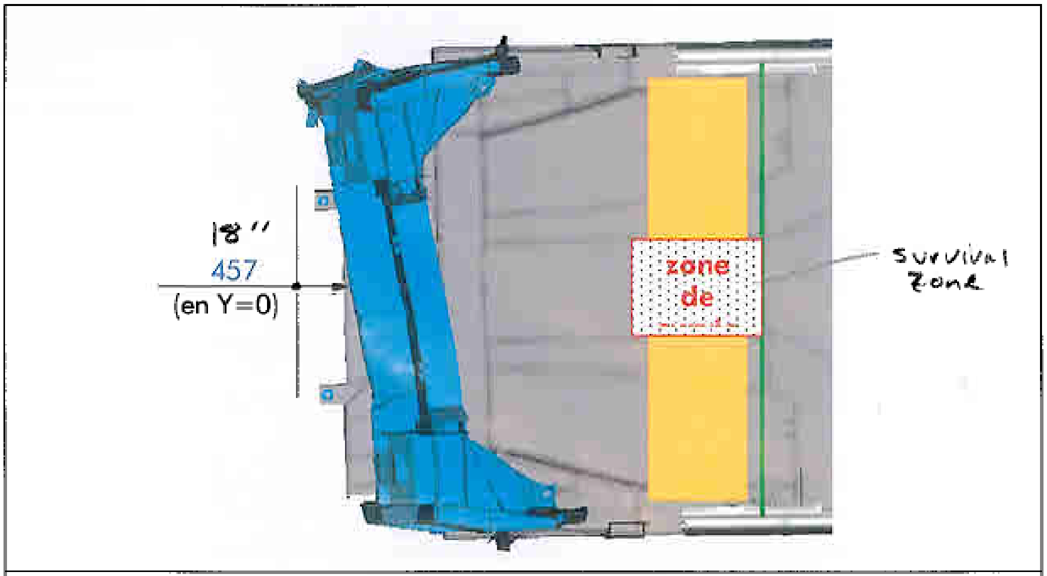


Fig. 98_ Déformée du bouclier de cabine à 250 ms

Deformation of the cab shield at 250 msec

Figure 45 - Cab Shield Deformation in Alstom Trainset - Tank Trailer Impact (15 Degrees)

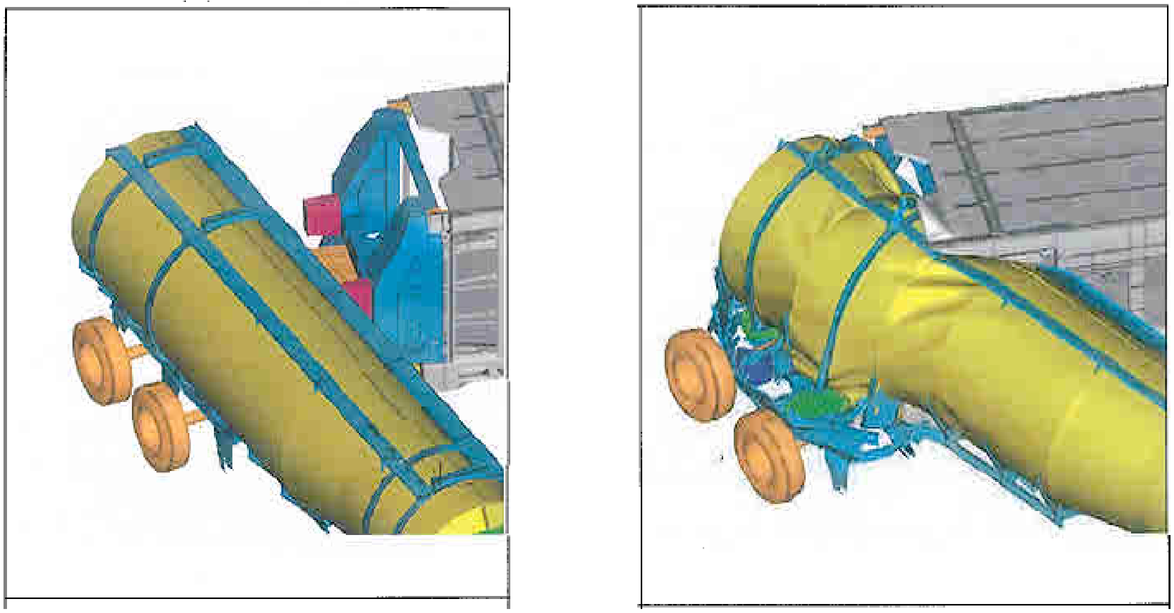


Figure 46 - Pre- and Post-Impact Alstom Trainset - Tank Trailer (15 Degrees)

5.6. Collision of an 8-Car EMU Train with a Standing-Locomotive-Leading Train

As part of the effort to investigate crashworthiness of the European EMUs for U.S. operation, the FRA asked the Caltrain team to conduct analysis for impact with a passenger locomotive, which might be at the end of a conventional train. Such a collision scenario was developed by the CEM Working Group and incorporated into the technical specification for the SCRRA cars referred to earlier. In that specification, a cab car-leading, six car train collides with a standing locomotive-leading six car train at a speed of 25 mph. One-dimensional lumped mass simulations are permitted to demonstrate that there is no loss of occupant volume. The specification also requires that three-dimensional, dynamic finite element analysis be conducted for the detailed interaction between the cab car and the locomotive. In this case, an idealized, rigid, locomotive profile is used. The FRA requested the Caltrain team to investigate the detailed collision interaction between an EMU and a **deformable** locomotive. All of these types of analyses were conducted and are summarized here. The one-dimensional analysis was conducted after the crush response was obtained from the three-dimensional finite element analysis. In addition, an analysis was conducted to determine the maximum crush load for an EMU to check the assumptions used in the one-dimensional analysis.

A three-dimensional finite element analysis conducted by Alstom [Ref 15] to determine the EMU crush response for the rigid locomotive profile used the following parameters (see Figure 47):

- 4-Car train impacting a standing locomotive at 22.4 mph
- Moving train weight = 640,000 pounds
- Locomotive weight = 280,000 pounds
- The locomotive end is rigid with the profile from the SCRRA specification
- The locomotive is allowed to move longitudinally after impact.

Figure 47 shows the relative scale and positions of the two bodies at the impact interface. Note that the locomotive end sill is relatively high, but does contact some of the crushable elements. The locomotive front plate contacts the lower crushable elements, and the coupler should activate the pushback mechanism; however, the EMU coupler was not present in this analysis. The upper-most elements are not directly engaged because the locomotive surface includes no superstructure.

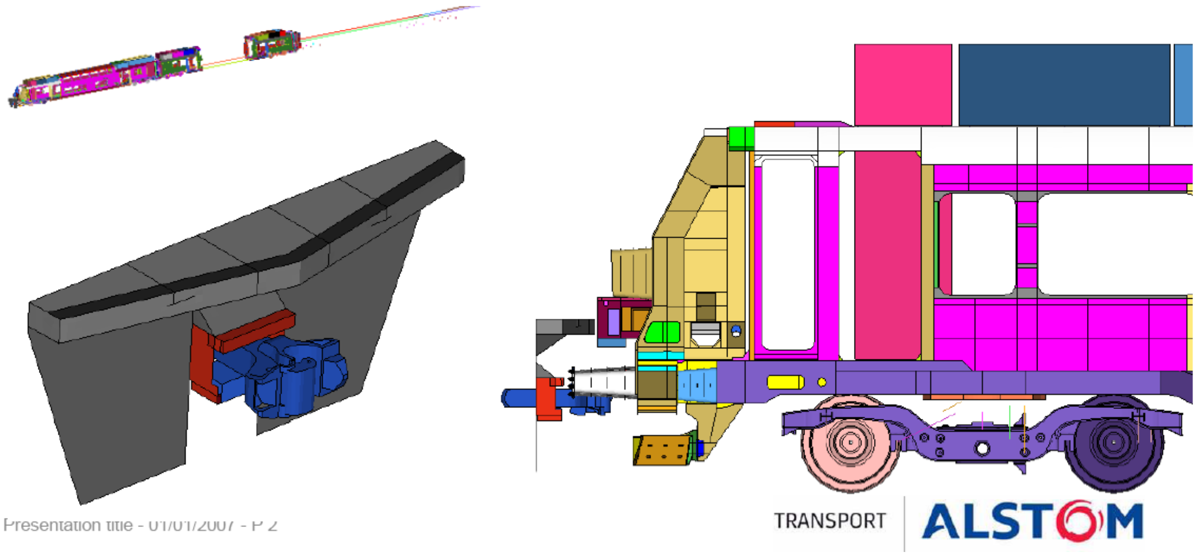


Figure 47 - **EMU- Locomotive Collision Interface**

The most important result from the Alstom analysis was the load-crush response shown in Figure 48. A maximum force of approximately 1.6 million pounds was sustained, but more importantly, the cab was allowed to crush about 28 inches while building up to that force, and crushed an additional 6 inches after the initial peak load was reached.

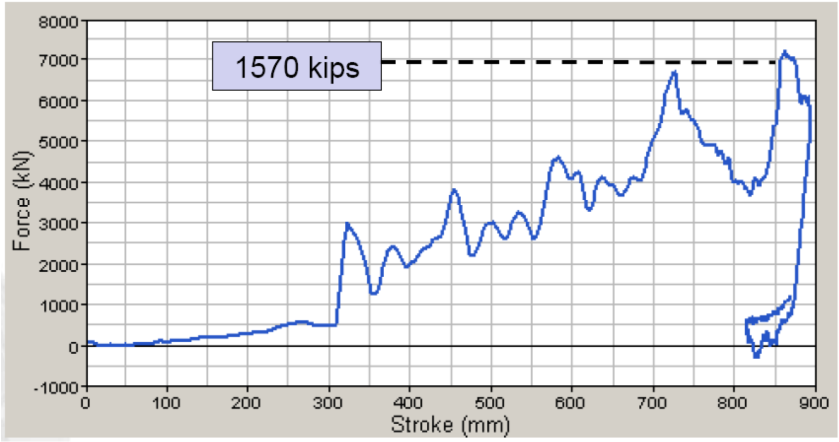
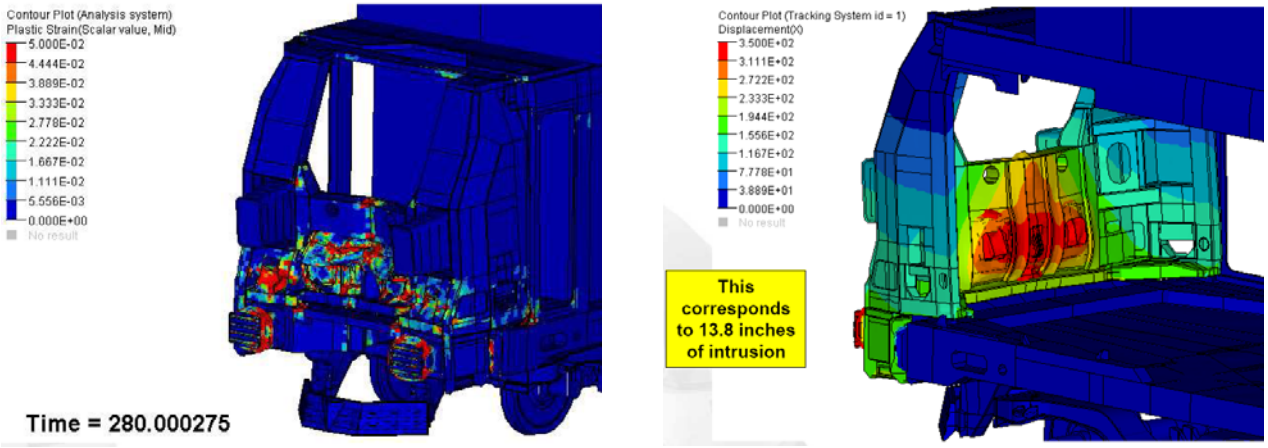


Figure 48 - **EMU- Rigid Locomotive Collision Interface**

Figure 49 shows the calculated deformation and plastic strain in the cab end. The deformation was concentrated in the crush zone region. Note that the cab bulkhead undergoes the high strain, but remains intact. Also note that the upper absorbers undergo no strain, as they never engage the locomotive. The 13.8 inches of intrusion into the cab is 1.8 inches more than would be allowed by EN15227 for a like-train impact, indicating that the operator's survivable space has been limited to about 10 inches in front of the seat, rather than the required 12 inches.



This corresponds to 13.8 inches of intrusion

Figure 49 - Deformation in the Alstom EMU from Impact with the Rigid Locomotive Surface.

Siemens conducted three-dimensional finite element analyses to investigate the interaction between one of their EMUs and a deformable locomotive. In this case, the model for the deformable locomotive was obtained from the Volpe Center. It is the model that was used in the TTCI train-to-train collision test simulations. [Ref 16] Siemens ran the analysis for a collision speed of 25 mph. The deformed shape and the resulting load-crush curves are shown in Figures 50, 51 and 52. [Ref 17]

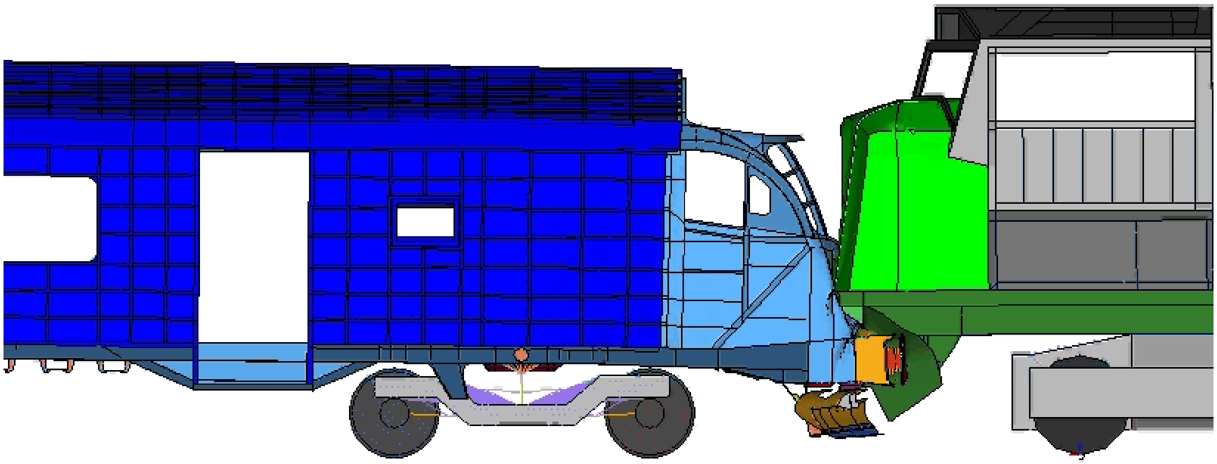


Figure 50 - Deformed configuration of the EMU-to-Deformable Locomotive Collision

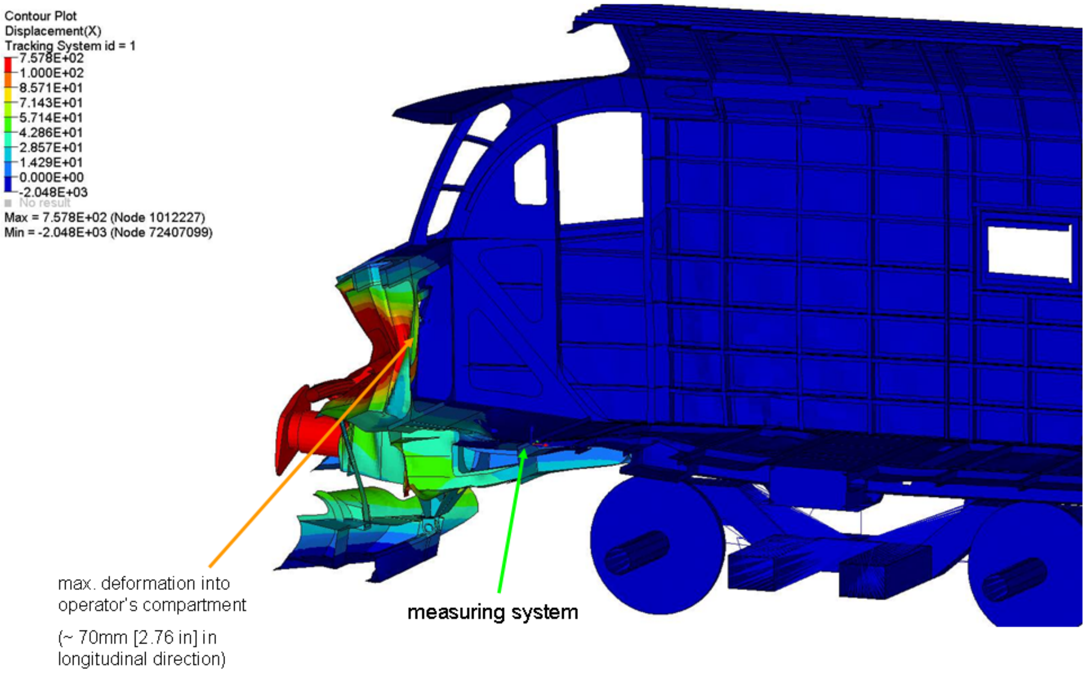


Figure 51 - **Internal View of the Deformation Caused by Impact with the Deformable Locomotive**

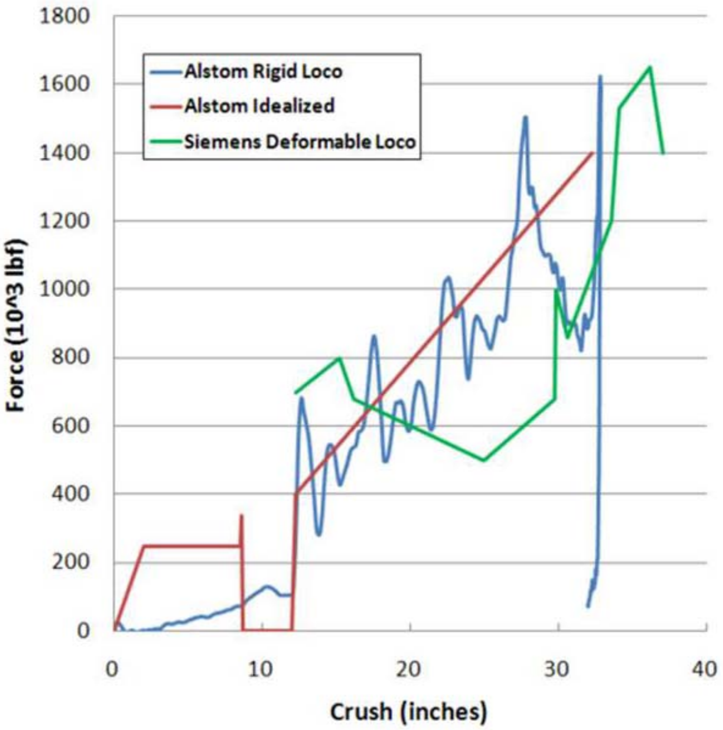


Figure 52 - **Calculated Load-Crush Curve for the Siemens EMU-Deformable Locomotive Impact Case in Comparison to the Alstom EMU-Rigid Locomotive Case**

Siemens pointed out that the crush elements on the EMU could be relatively easily positioned to promote better crush. In addition, real locomotives have an end plate that is reinforced from behind by struts, stiffeners, and stairwells, which would also improve crush response. The model of the deformable locomotive includes no front plate reinforcement. These factors would certainly move the calculated load-crush curve close to or above the curve used in the one-dimensional analyses and, therefore, result in the same conclusion about safe closing speed.

Siemens also conducted an analysis to obtain an estimate for the crippling load (that is, the maximum crush load) of one of their single level EMUs. A single car was simulated to impact a rigid, flat surface at a high enough speed to reach the crippling load. Figure 53 shows the resulting load-time plot and Figure 54 shows the calculated deformation at the point corresponding to the maximum load.

The crippling load is approximately 7800 kN or 1750 kips. This load is between the 1600 and 2000 kip crippling loads assumed for the one-dimensional collision dynamics analysis described below. The 1600 kip load determined the outcome of those calculations, so the crippling load analysis provides support for the assumptions used.

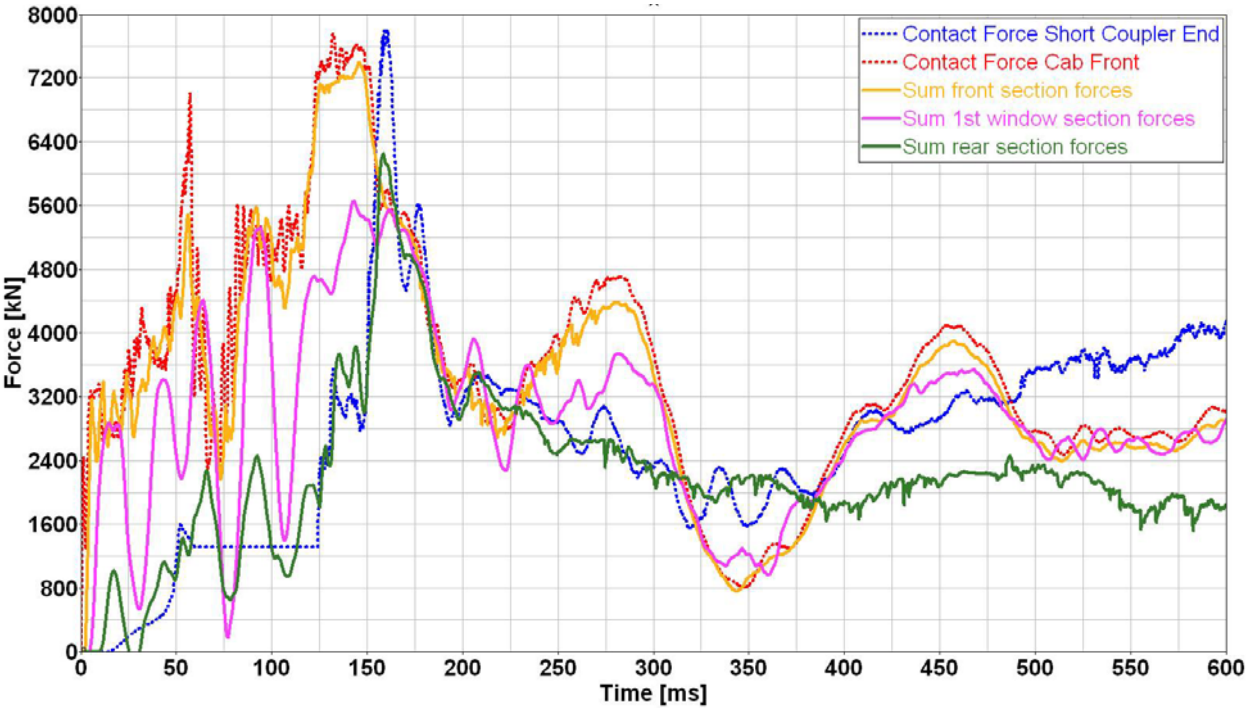


Figure 53 - Calculated Load-Time Plot for the EMU-Flat Surface Impact Case; the Contact Force Cab Front is the Curve of Interest Here

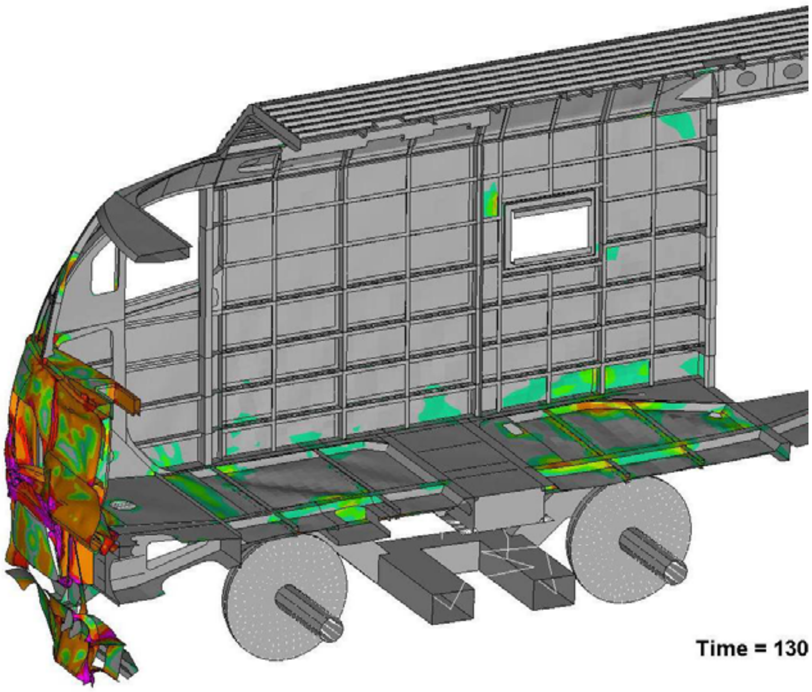


Figure 54 - Calculated Deformation for the EMU-Flat Surface Impact Case Near the Point in Time Corresponding to the Crippling Load

The one-dimensional analysis conducted by the Caltrain team used the model described in the previous section with the parameters shown in Figure 55 and the crush curves shown in Figure 56. Again, the crush curve for the conventional car is derived from FRA full scale tests, but is intended only to represent the maximum load capacity of the car. The crush response for the EMU cab end crush zone is a simplification of the response in Figure 48 (see Figure 52) with the expectation that the maximum load (not reached in the analysis done to generate that curve) is close to 2,000,000 lb. The lower maximum load used for the EMU non-cab ends was selected to be consistent with the similar assumption of lower strength used by the Volpe Center in *Effectiveness of Alternative Rail Passenger Equipment Crashworthiness Strategies.* [Ref 18].

8-Car EMU train (two 4-car sets) is moving at impact
EMU train weight = 1,280,000 pounds

Locomotive-hauled train is stationary at impact
Locomotive weight = 280,000 pounds
Coach weight = 160,000 pounds (5 coaches)
Locomotive end frame is rigid (retains shape during impact)
Locomotive-hauled train is allowed to move after impact

Figure 55 - Dissimilar Train Impact Scenario

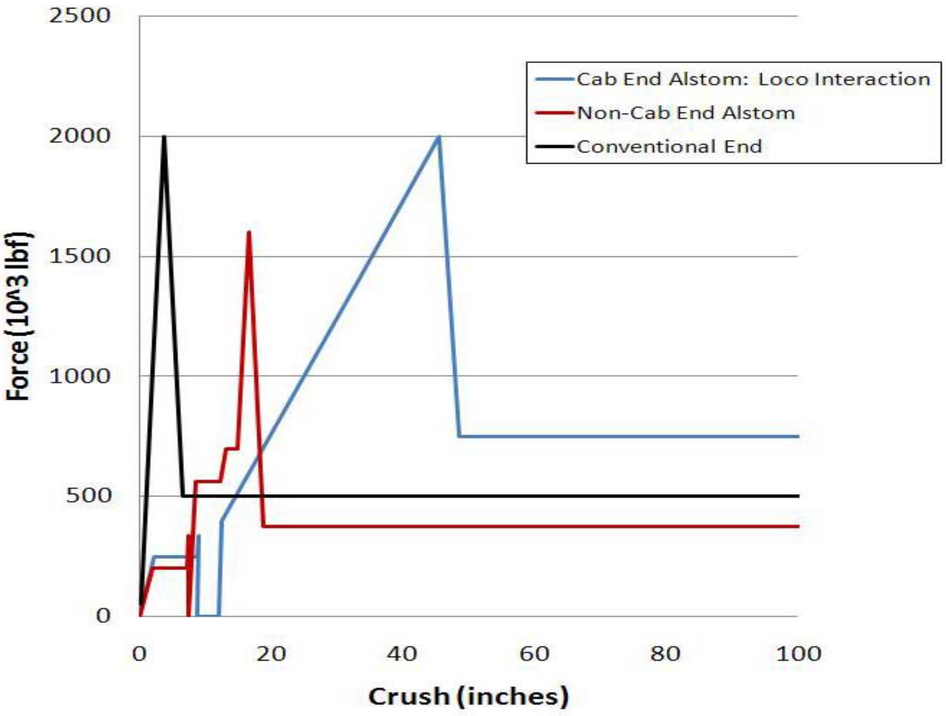


Figure 56 - One-Dimensional Train-to-Train Crush Curves

Calculations were carried out for different collision speeds, from which it was determined that the maximum collision speed at which occupant volume was preserved was 20 mph. Figure 57 shows the calculated crush at each vehicle end (it is the same on each side of a coupled interface) for the 20 mph case. If the speed were increased, the allowable crush would first be reached at the intermediate EMU car ends, because the simulated crush strength is lowest there.

Secondary impact velocities for the 20 mph impact are shown in Figure 58. They are about 16 mph for the cab car and they are below 15 mph for the trailer cars. Although there are currently no Federal or APTA limits on secondary impact velocity for this type of collision scenario, the allowable values in the SCRRA specification are 20 mph for the cab car and 15 mph for the trailer cars.

Figure 59 shows crush results for key vehicle ends as a function of collision speed. Above a speed of 20 mph, the cab energy absorbers are exhausted. At 25 mph, the cab occupant volume is reduced beyond allowable limits, but only by about five inches. Above 25 mph, the rear of the cab car reaches a point at which it can no longer resist the crush load applied by the rest of the train and the occupant volume begins to decrease at a rapid rate. By 27 mph the calculated crush is over 200 inches. The exact crush value is not as important as the fact that the car body is no longer able to resist the crush load in the closing speed above 25 mph.

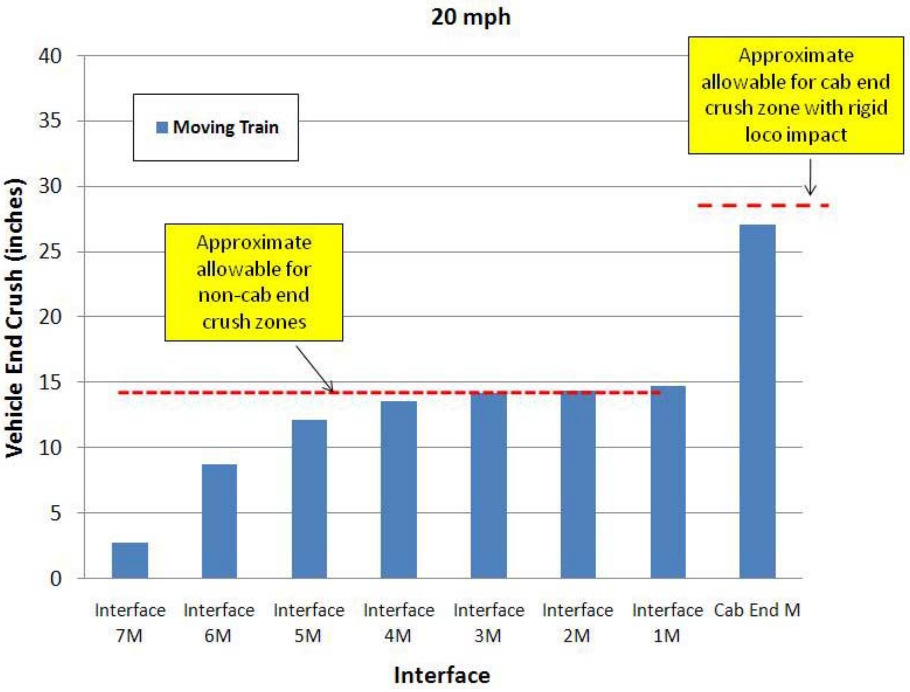


Figure 57 - One-Dimensional EMU Train-to-Locomotive Leading Compliant Train Crush Curves

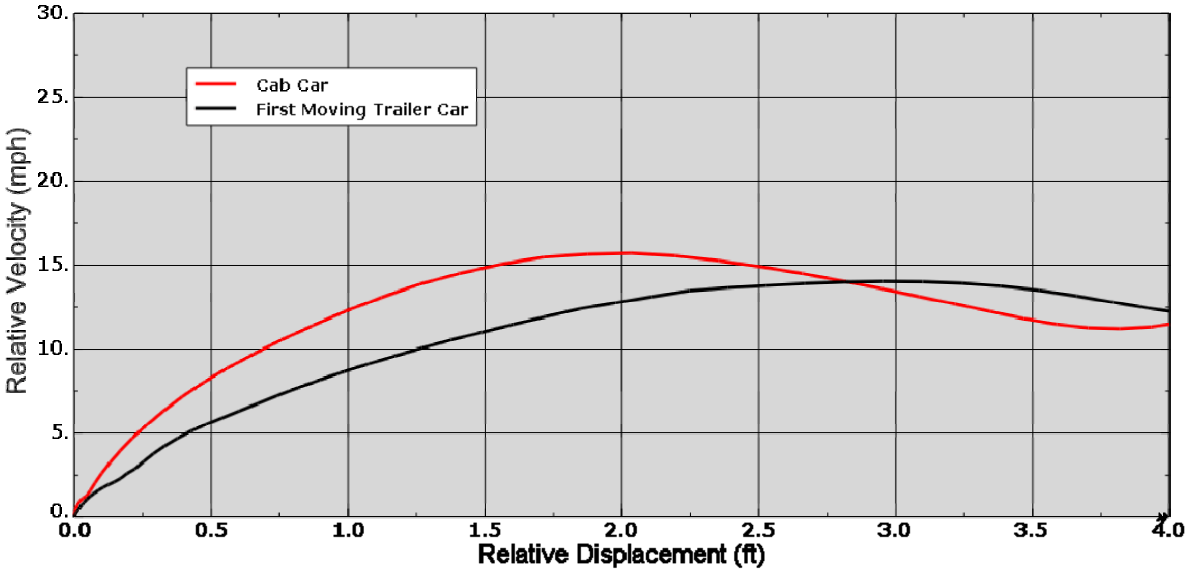


Figure 58 - EMU-Locomotive Collision Secondary Impact Velocities

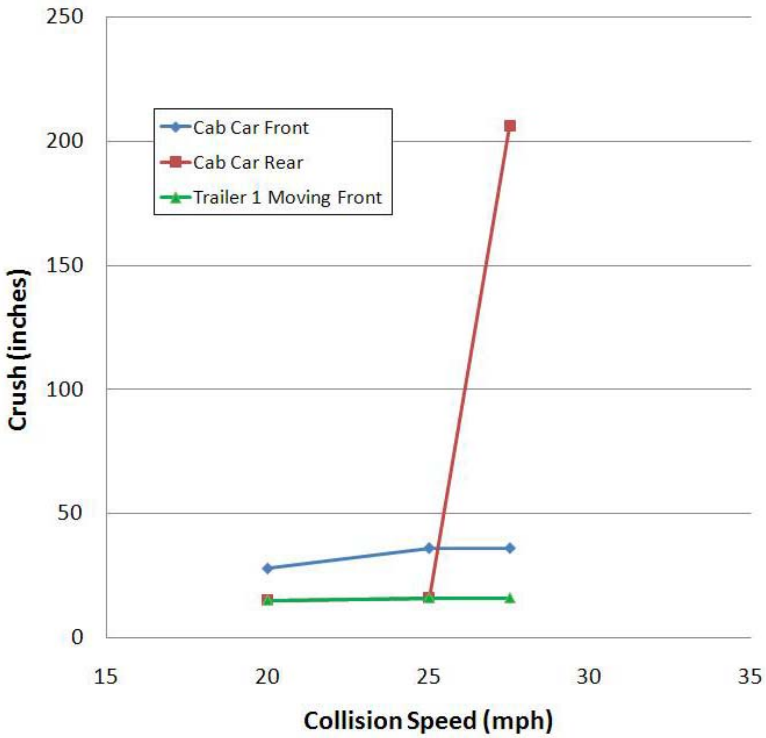


Figure 59 - Crush in EMU Car Ends for the EMU-Locomotive Collision at Various Speeds

5.7. Compliant Train Collisions

The Caltrain team did not perform analyses for collisions between compliant trains. However, The Volpe Center has performed analyses and tests on such rolling stock and some of their work is referenced here for comparison to the EMU train-to-train analysis results.

Some of the implications of the FRA/Volpe work are summarized in *Effectiveness of Alternative Rail Passenger Equipment Crashworthiness Strategies* [Ref 18]. This paper provides estimates of the safe operating speed for a variety of simulated compliant conventional trains and CEM trains. Safe operating speed is meant to be the speed below which there is no significant loss of occupied volume. The scenario analyzed is a six vehicle moving train, with a locomotive on one end, either the lead or trailing end, colliding with a six vehicle standing train with a locomotive at the impacted end.

Figure 60 shows the results for the compliant, conventional train configurations. They indicate that there is a substantial loss of occupant volume above a speed of 15-20 mph for the cab leading configuration, and above 25-30 mph for the locomotive leading configuration. This is in the same range as the value calculated for the EMU configurations being considered by Caltrain, indicating that the EN15227 equipment provides a level of crashworthiness comparable to that provided by compliant vehicles in a train-to-train collision.

Figure 60 - **Compliant Train Collision Crush at Various Speeds (Impacting a Standing Locomotive and Coaches)**

5.8. Collision of Like EMU Trainsets

Three analyses were performed for the case of an EMU train colliding with a like EMU train:

- 4-Car Train on 4-Car Train (Alstom standard analysis) [Ref 19]
- 12-Car Train on 12-Car Train (Alstom prepared for separate client) [Ref 20]
- 8-Car Train on 8-Car Train (prepared by Caltrain team) [Ref 21]

The primary configuration of interest is the 8-on-8 configuration, because this is the manner in which Caltrain is most likely to operate. The analyses conducted by Alstom existed prior to the Caltrain crashworthiness investigation effort and are included here for reference.

The 4-on-4 and 12-on-12 calculations conducted by Alstom are actually three-dimensional finite element analyses with simplified trailer car models that also provided some baseline performance characteristics useful as input for a one-dimensional analysis conducted by the Caltrain team. The idealized crush curves from the Alstom analysis are shown in Figures 61 and 62. The stepped response corresponds to the sequential interaction of absorbers. In the case of the cab end, crush occurs in the push back coupler, followed by the buffer absorbers, the upper absorbers, and the side structure absorbers. The coupled interface response corresponds to both ends and includes the push back connection, followed by the anticlimber absorbers and the car body absorbers.

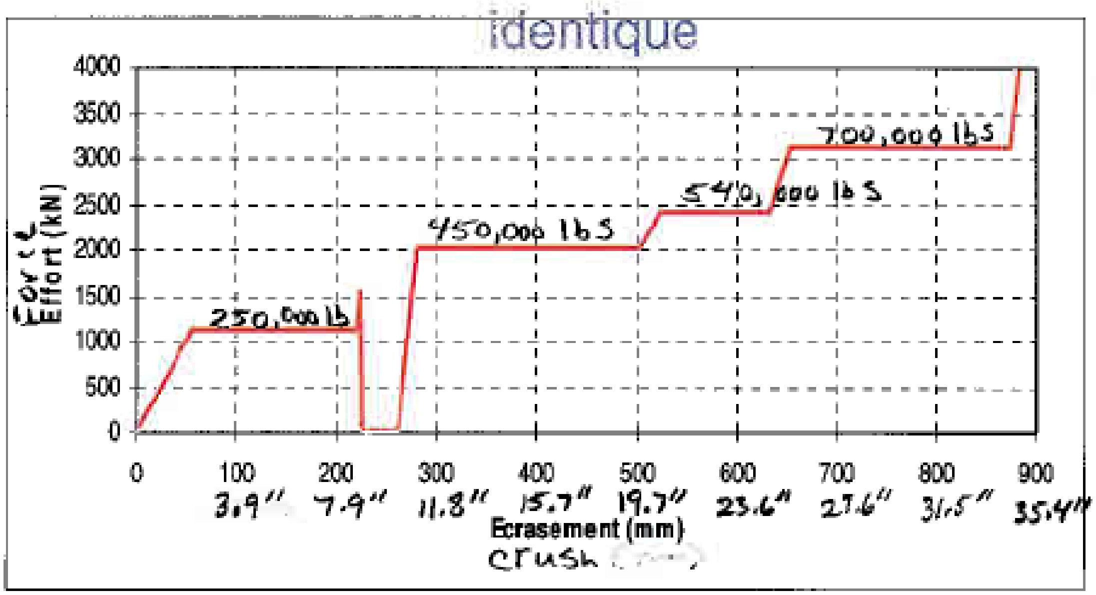


Figure 61 - 12-Car Like Train Collision Cab Crush Curve

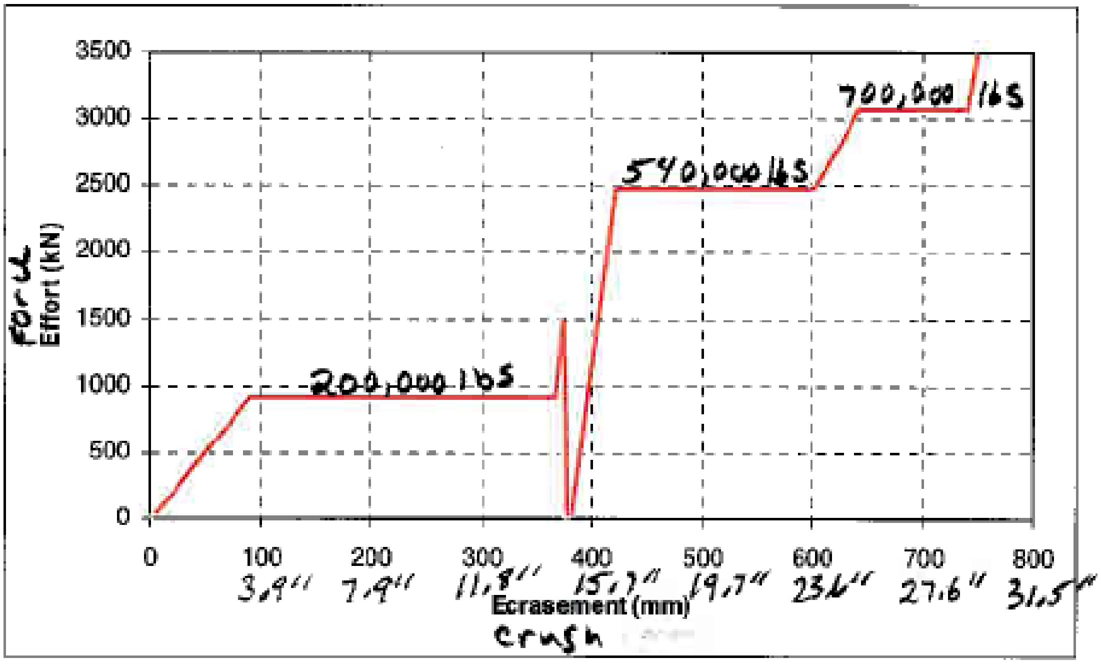


Figure 62 - 12-Car Like Train Collision Intermediate Connection Crush Curve

Damage sustained in the 4-on-4 simulation was limited to replaceable elements, by design. The initial speed of each train was 11.25 mph for a closing speed of 22.5 mph, per EN15227. Figure 63 shows an example of the calculated interaction between the impacting car ends.

Figure 63 - Pre- and Post-Impact Alstom Trainsets

Alstom did not report secondary impact velocities for passengers, but did report a 2.2 g deceleration of the cab car, which is below the generally accepted criterion for survivability of passengers.

At the request of a European customer, Alstom prepared a second analysis with twelve-car trains. This proved valuable because it more completely exercised the CEM elements. Each train weighed 1.8 million pounds (average 150,000 lb/car), and had an initial velocity of 11.2 mph. The maximum crush of the leading cab was 28.1 inches. A crush of 34.3 inches is allowed, based on the EN15227-mandated survival space required for the operator. Thus, this test did not push the limits of the cab, nor any of the between-car connections. .

The Caltrain team prepared a one-dimensional analysis to investigate the 8-on-8 configuration expected to be commonly used for the Caltrain system. Using the crush curves previously shown, it was determined that the trainset could withstand a 25 mph impact without compromising the occupied space or exceeding a secondary impact velocity of 15 mph over 2 feet; this is the criterion used in the SCRRA specification. Figure 64 shows the crush at every interface in the two trains. (This is the crush at each end.) Figure 65 shows that the secondary impact velocity is well below the 15 mph limit.

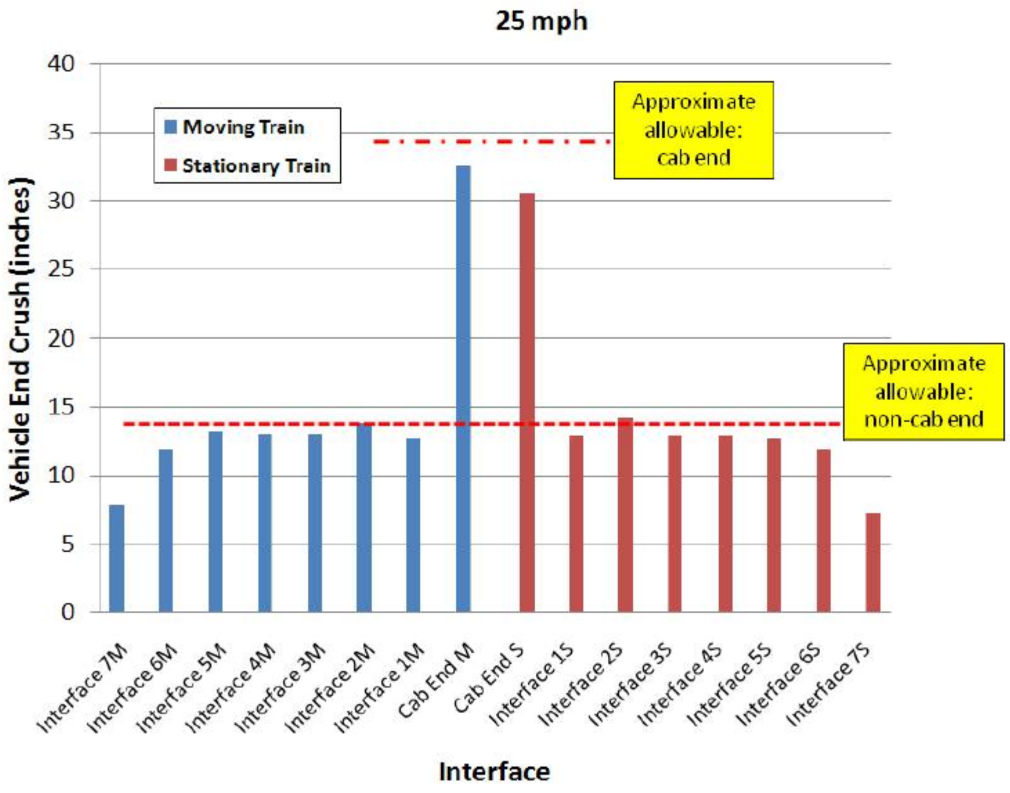


Figure 64 - **8-Car 25 mph Like Train Impact Crush by Interface**

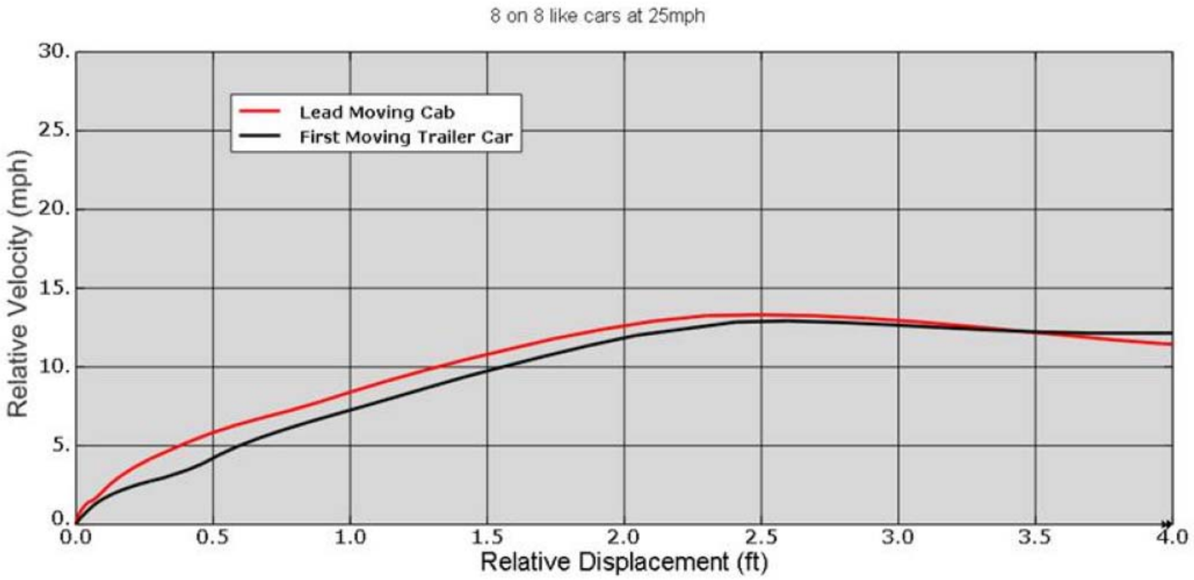


Figure 65 - **8-Car 25 mph Like Train Impact Secondary Impact Velocity**

5.9. Post-Derailment Collision with a Stationary Object

Impact between a derailed EMU train with a stationary wayside object, such as a bridge abutment, is one of the collisions identified in the hazard analysis. The Caltrain team did not carry out analysis for this particular case, but instead infer the consequences from analyses already conducted. Impact between a train and a flat, rigid surface that is perpendicular to the line of the train is equivalent to impact between identical trains each moving at the same speed. The one-dimensional analysis carried out by the Caltrain team for the 8-on-8 configuration indicate that trains designed to EN15227 can sustain a collision between like trains with a closing speed of 25 mph. Thus, one can infer that these trains can sustain an impact with a rigid surface at 12.5 mph.

Making a comparable assessment for compliant trains is difficult because there are evidently no results available for cab car leading trains colliding with like cab car leading trains. Instead, collision energy is used to approximate the safe speed for collision with a rigid object.

A full-scale test was conducted on a single, multilevel car by FRA/Volpe, in which the 95,400 lb car was impacted into a rigid wall at 36.6 mph. [Ref 22] The collision energy associated with this impact is 4.3×10^6 ft-lbf. There was about 2 ft of crush so that the occupant volume was beginning to be compromised. The same collision energy is obtained if a conventional train with a leading cab car (160,000 lb), four coach cars (each 160,000 lb) and a trailing locomotive (280,000 lb) collides with a rigid wall at 11 mph. This indicates that European EMU equipment satisfying EN15227 and operated in an eight car configuration will have comparable crashworthiness to the compliant equipment configuration for impact into a stationary, rigid, wayside object.

6. Interpretation of Results for Hazard Analyses

Analyses have primarily been directed towards three mishap categories:

- Grade crossing collisions
- Train-to-train collisions
- Post-derailment impacts

The following subsections provide an interpretation of the previously-presented results with respect to two goals. First is to establish the outcome category for specific mishaps in the hazard analysis and second, to give some indication of the system level safety with an EN15227-compliant EMU operating on an FRA-compliant railroad. The current Caltrain hazard analysis categorizes mishap outcomes as shown in Table 7. Ultimately, the results presented in this report must be distilled to provide outcomes that match one of the Table 7 categories.

Table 7 - Mishap Outcome Severity Classifications

Category Title	Severity
Catastrophic	People – Loss of life and numerous major injuries CEM Vehicle – Cab or passenger volume is significantly compromised. CEM Vehicle damaged beyond repair
Critical	People – Loss of life and major injuries CEM Vehicle – Cab or passenger volume is partially compromised. Major damage to CEM Vehicle
Serious	People – Minor injuries and limited major injuries CEM Vehicle – Major Damage to Exterior of Vehicle. Occupied Volume not Compromised
Marginal	People – Minor injuries requiring medical treatment away for the scene of the accident CEM Vehicle – Minor Damage to Exterior of Vehicle. Occupied Volume not Compromised
Negligible	People – No or minor injuries only requiring first aid treatment at the scene CEM Vehicle – No or minimal repairs required to Exterior of Vehicle. Occupied Volume not Compromised

6.1. Grade Crossing Collisions

There are three scenarios to be summarized. They are a collision with a small object like an automobile, a collision with a large deformable object like a tank truck, and a collision with a rigid body like the steel coil. Our calculations and review of the available literature indicate that both the FRA-compliant cab car and the EN15227-compliant EMU perform favorably and similarly in all three categories, with one exception. Limited results exists for the FRA-compliant cab car in a 70-mph impact with the deformable tank truck, as only calculations by the Caltrain team exist at this speed. Table 8 provides a summary of outcomes for use in the hazard analysis.

Table 8 - Grade Crossing Collision Outcomes with Respect to Railcar and Passengers

Mishap	General Outcome	EMU Category	Compliant Category
Train strikes automobile or large piece of debris on track at up to 79 mph	Minor damage to cab requiring repair prior to placing back in service (pilot). No injuries to crew or passengers	Marginal	Marginal
Train strikes trailer with rigid object on deck at up to 21 mph	Damage to cab limited to fiberglass cowlings and crushable elements in EMU versus likely replacement of collision or corner post in compliant cab. No injuries to crew or passengers.	Serious	Serious
Train strikes deformable semi trailer at up to 50 mph*	Damage to railcar limited to replaceable elements for EMU cab versus replacement of end sheet, collision and corner posts for compliant cab. Minor injuries to operator, no passenger injuries.	Serious	Serious

* The Caltrain EMU will survive a 68 mph collision per EN15227 as discussed below.

Siemens and Alstom analyses showed that the “serious” outcome can be maintained up to 70 mph for the EN15227 test case. Caltrain analysis indicated that a compliant cab would not maintain a “serious” outcome at 68 mph and Volpe did not report results above 53 mph. The Caltrain EMU procurement specification will require compliance with the EN15227 truck impact requirement at speeds up to 68 mph

For the Caltrain waiver, it is the responsibility of the petitioner to prove that safety is not compromised at the system level. This analysis does not examine the system as a whole, but only the vehicles. These analyses, performed by multiple organizations, show that the EN15227-compliant EMU performs at least as well in all grade crossing scenarios. Thus, it is not necessary to make alterations to other parts of the system to maintain the same level of system safety.

6.2. Train-to-train Collisions

This analysis could consist of a matrix of collisions between FRA-compliant and EN15227-compliant vehicles with each other and with like trains. However, as will be shown here, there is very little difference in the outcome of the train-to-train collisions with respect to vehicle type. Drawing from analyses performed by Siemens, Alstom, the Caltrain team, and The Volpe Center, the most quantifiable data point is the speed at which the vehicles can no longer resist a crush load during full-train collisions. While this is idealized, in that these types of collisions rarely happen in perfect alignment, the analysis provides a good measure of the crush resistance of each vehicle type. Figure 66 provides a summary of calculated occupant volume crush values at different speeds, and indicates where the outcome would be considered serious, critical, or catastrophic. Results for the conventional trains were obtained from Jacobsen, et. al. (2006) and the results for the EMU were obtained from Caltrain analyses.

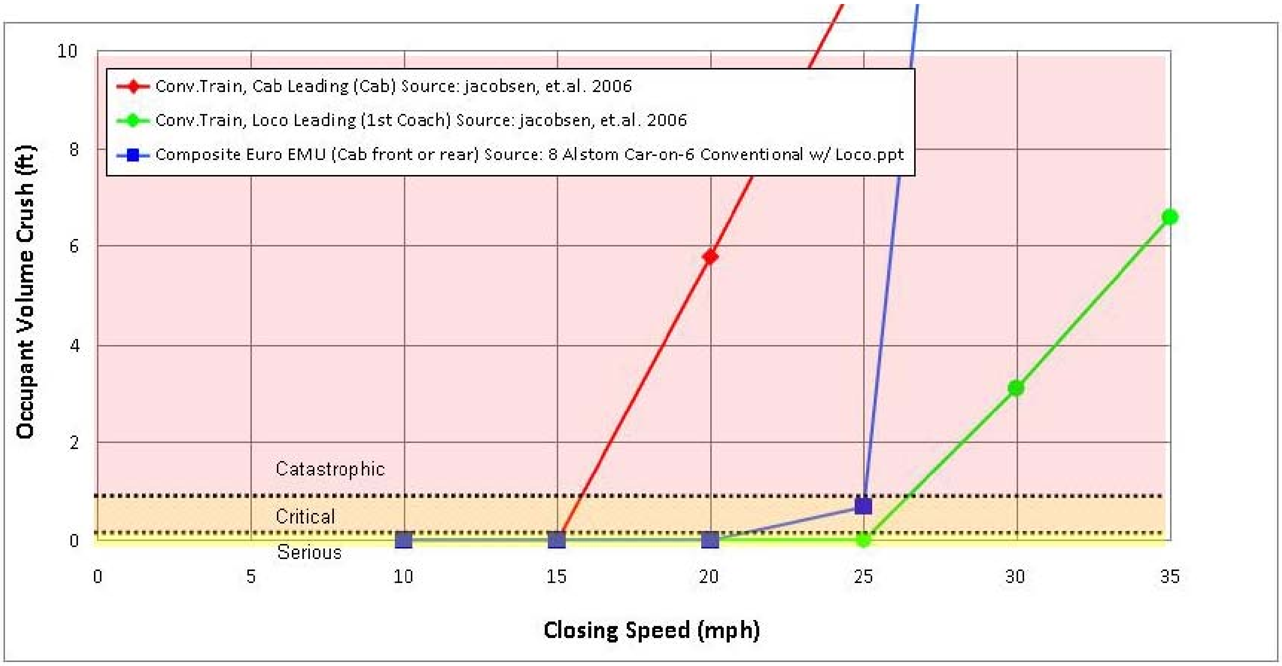


Figure 66 - Train-to-Train Collision Crush at Various Speeds

The analyses performed by Volpe for cab-car-leading and locomotive-leading trains impacting a locomotive-led train seem to bracket the results for the EMU. However, the results for the locomotive-leading case are actually very similar to the EMU case. At speeds above 25 mph, the results would be classified in the hazard analysis as catastrophic because passenger-occupied space is compromised, implying multiple cases of serious injury or loss of life. At speeds below 15 mph, the results would be classified as serious for all vehicle designs, as there would be no loss of operator or passenger occupied space. In the 15 mph to 25 mph, each vehicle type undergoes a transition in which some space is lost. For a typical cab car, the operator's space is compromised above 15 mph, indicating a critical outcome, and at about 18 mph, the passenger-occupied space is compromised. For the EMU, the operator's space is compromised above 20 mph, at which the outcome is considered critical. It is unknown at what speed the cab space in the locomotive is compromised, so the transition from serious to critical is unknown. Table 9 summarizes these outcomes somewhat independent of the type of train impacted.

Table 9 - Train-to-Train Collision Outcomes with Respect to Vehicles and Passengers

Mishap	General Outcome	EMU Category	Compliant Category
Train strikes standing train at up to 20 mph*	Occupied spaces not compromised	Serious	Serious
Train strikes standing train at speeds above 20 mph*	Occupied spaces compromised	Catastrophic	Catastrophic

* Results vary by a few mph by vehicle design but are close enough for the use of the hazard analysis

These analyses, performed by multiple organizations, indicate that the EN15227-compliant EMU performs at least as well as an FRA-compliant cab car or coach in all train-to-train collision scenarios. Thus, it is not necessary to make alterations to other parts of the system to maintain system level safety. However, it is clear that above about 25 mph, a means of mitigating the risk of serious injury or death to passengers is desirable. This was recognized by the FRA in a recent report and letter to Congress, as well as the recent Railway Safety Act requiring positive train control. The argument presented in these documents is the same as the approach that Caltrain proposed at the beginning of this project, which is the use of a positive train control system to greatly reduce the probability of train-to-train collisions.

6.3. Post-Derailment Impacts

The difference between outcome classifications for all train types is within one or two mph, as shown in Table 10. Thus, no special mitigation is necessary to maintain Caltrain's current level of system safety while operating EMUs, with respect to this hazard. The speeds at which occupied space is compromised are very low (on the order of 12 mph). This is due to the nature of the analyses and test procedures. The fixed object is truly fixed, offering no energy absorption, where a structure on the railroad, such as a bridge pier, might actually absorb some energy as it sustains damage during the impact. Nonetheless, as with train-to-train collisions, these types of impact need to be avoided, as it is clear that the risk cannot be mitigated in any substantial way through vehicle structural enhancements. While frequency of such impacts is already extremely low, the probability of such events can be reduced at the design level, by paying attention to special track work near such fixed objects, and at the operating level through good track and mechanical equipment maintenance practices. Table 10 generalizes the results for train-to-fixed object collisions.

Table 10 - Train-to-Fixed Object Collision Outcomes

Mishap	General Outcome	EMU Category	Compliant Category
Train strikes fixed object up to 12 mph*	Occupied spaces not compromised	Serious	Serious
Train strikes fixed object above 12 mph*	Occupied spaces compromised	Catastrophic	Catastrophic

* Results vary by a few mph by vehicle design but are close enough for the use of the hazard analysis

7. Risk Mitigation for Waived Regulations

Caltrain intends to petition the FRA for waivers for up to five regulations, depending on the outcome of proposed rulemaking:

- 49 CFR 238.203 Static End Strength
- 49 CFR 238.205 Anti-Climbing Mechanism
- 49 CFR 238.207 Link Between Coupling Mechanism and Car Body
- 49 CFR 238.211 Collision Posts
- 49 CFR 238.213 Corner Posts

The following measures are proposed to mitigate any risk of operating equipment under waiver:

System-wide Measures

- Positive Train Control meeting FRA regulations currently under development
- Temporal separation of freight and passenger trains
- Continuous improvement of grade crossing protection systems
- Over-dimensioned lading detection in strategic locations

Rolling Stock Measures (by procurement specification)

- EN12663 PII Compliance
- EN15227 CI Compliance with following specifics:
    - Train-to-train collision scenario with 8-car like trains (22.5 mph)
    - Truck impact speed 110 km/hr (69 mph)
- Additional train-to-train impact scenario
    - 8-car EMU at 20 mph impacts locomotive at the head of a stationary 5-car train
        - EN 15227 performance criteria for train-to-train collision apply with one exception. Strains in excess of 10 percent would be reviewed on a case-by-case basis.
- Minimum car body ultimate buff (buckling) strength of 1.3 million pounds
    - Maximum load resisted while buckling or crushing
- Show that the train-to-train impact scenarios above do not result in overriding or bypass at the impact interface (cab end) as well as at the intermediate connections within the train
- Provide calculations showing the vertical and horizontal strength of all elements acting to restrain the vehicles during such impacts
- Compliance with the FRA collision post “proxy object cart” impact requirement currently proposed for 49 CFR 238.205 Appendix F
- Calculations showing the amount of deformation of the corner structure of the rail car when the static loads prescribed by 49 CFR 238.213 are applied does not compromise the occupied space

7.1. 49 CFR 238.203 Static End Strength

49 CFR 238.203 requires the car frame to resist an 800,000-pound compressive (buff) load on the line of draft, without permanent deformation. This requirement is directed mainly towards train-to-train crashworthiness. European EMUs are designed with CEM to specifically address collision scenarios that would otherwise result in a loss of occupied space. It is not practicable to modify a European EMU to meet the 800,000-pound buff strength requirement. This level of design change would not be feasible for a small order, and to require compliance would result in no bids being received. Thus, it is necessary to mitigate any risk through other means. The combination of a positive train control system and EN15227 compliance with CEM will reduce the probability of an impact and the severity of the outcome to the degree necessary to maintain Caltrain's current level of system safety. **Thus, a waiver for 49 CFR 238.203 will be requested.**

Multiple analyses have been offered in this report in an effort to assist Caltrain and the FRA in determining overall occupant volume strength. These analyses indicate that, collisions between like EMU trains and between EMU and locomotive-hauled trains at closing speeds at or below 20 mph are survivable by passengers and crew, and that the performance of EMUs is at least equal to compliant equipment in these scenarios. The use of a positive train control system should greatly reduce the probability of higher speed collisions in which neither the EMU trains nor compliant equipment can prevent the loss of occupied space.

It can be shown that the most quantifiable data point is the speed at which the maximum force required to crush the car body is reached during full-train collisions. At this force level, the body will continue to plastically deform without providing a substantial increase in force. While this is idealized in that these types of collisions rarely happen in perfect alignment, the analysis is a very good measure of the bulk strength of each vehicle type. Figure 66 provided a summary of occupant volume crush values at different speeds, and indicates where the outcome would be considered **serious** (occupied space maintained, minor injuries, no loss of life), **critical** (cab space compromised, passenger space maintained, limited major injuries, possible loss of life), or **catastrophic** (passenger space compromised, loss of life, multiple major injuries).

The analyses performed by The Volpe Center for cab-car-leading and locomotive-leading trains impacting a locomotive-led train seem to bracket the results for the EMU. However, the results for the locomotive-leading case are actually very similar to the EMU case. At speeds above 25 mph, the results would be classified as catastrophic because in addition to the cab, passenger-occupied space is compromised, implying multiple cases of serious injury or loss of life. At speeds below 15 mph, the results would be classified as serious for all vehicle designs, as there would be no loss of operator or passenger occupied space. In the 15 mph to 25 mph range, each vehicle type undergoes a transition in which some space is lost. For a typical cab car, the operator's space is compromised above 15 mph, indicating a critical outcome, and at about 18 mph, the passenger-occupied space is compromised. For the EMU, the operator's space is compromised above 20 mph, at which the outcome is considered critical. It is unknown at what speed the cab space in the locomotive is compromised, so the transition from serious to critical is unknown.

For the Caltrain waiver, it is the responsibility of the petitioner to prove safety is not compromised at the system level. This report does not examine the system as a whole, but only the vehicles. These analyses, performed by multiple organizations, indicate that the EN15227-compliant EMU provides the same occupied volume protection as an FRA-compliant cab car or coach in these train-to-train collision scenarios. Thus, it is not necessary to make alterations to other parts of the system to avoid compromising system-level safety. However, it is clear that above about 25 mph, a means of mitigating the risk of serious injury or death to passengers is desirable for EMUs and compliant equipment alike. This was recognized by the FRA in a recent report and letter to Congress [Ref 23], as well as the Rail Safety Improvement Act of 2008 [Ref 24] requiring positive train control. The argument presented in these documents is the same as the approach that Caltrain proposed at the beginning of this project, which is the use of a positive train control system to greatly reduce the probability of train-to-train collisions.

The Caltrain EMU specification will require the vehicle manufacturer to prove the following to address the 800,000-pound buff strength requirement. Analyses of the final design (after contract award) and test results must be submitted by the car builder for Caltrain and FRA review.

- EN12663 PII Compliance
- EN15227 CI Compliance with following specifics:
  - Train-to-train collision scenario with 8-car like trains (22.5 mph)
  - Truck impact speed 110 km/hr (69 mph)
- Additional train-to-train impact scenario
  - 8-car EMU at 20 mph impacts locomotive at the head of a stationary 5-car train
    - EN 15227 performance criteria for train-to-train collision apply with one exception. Strains in excess of 10 percent would be reviewed on a case-by-case basis.
- Minimum car body ultimate buff (buckling) strength of 1.3 million pounds
  - Maximum load resisted while buckling or crushing

7.2. 49 CFR 238.205 Anti-Climbing Mechanism

49 CFR 238.205 requires the car to be equipped with an anticlimbing mechanism that can withstand an 100,000-pound uplift. This requirement is directed towards preventing override in a train-to-train impact. The CEM design utilizes many components and features specifically designed to prevent overriding or telescoping. However, these elements are not designed to individually withstand a 100,000-pound vertical force as required by this CFR section, and re-design may substantially complicate CEM implementation. **Thus, a waiver for 49 CFR 238.205 will be requested.**

Inherently, CEM designs are intended to serve the function of anti-climbers, and can be much more effective than anticlimbers mounted on a compliant car. This is because CEM is meant to control the way that the energy is expended on impact, in all of the crushing of elements specifically designed for that purpose. The FRA's own research has concluded that CEM helps to prevent telescoping, and that railcars of a more rigid design can override or bypass each other laterally. Figures 25, 50, and 63 show how the deformable elements in the nose of the EMU provide anti-climbing protection. Overriding or bypassing is not seen, because the crushable elements conform to the shape of the opposing structure, effectively locking the two trains together.

The intermediate connections within the EMU train take advantage of an energy-absorbing drawbar connection and anticlimber/absorbers, and while some deformation of the structure in this area may take place, the vehicles stay connected, preventing override or bypass.

The Caltrain EMU specification will include the following requirements to address the 100,000-pound anticlimbing strength requirement:

- Show that during the train-to-train impact scenarios specified under report Section 7.1 above do not result in overriding or bypass at the impact interface (cab end) as well as at the intermediate connections within the train
- Provide calculations showing the vertical and horizontal strength of all elements acting to restrain the vehicles during such impacts

7.3. 49 CFR 238.207 Link Between Coupling Mechanism and Car body

49 CFR 238.207 requires the coupler carrier to withstand an 100,000-pound down force without yield. This requirement is also directed towards preventing override in a train-to-train impact. However, the CEM design requires that both the couplers and the intermediate drawbars be allowed to move longitudinally under a load that is large enough to begin activation of the energy absorbing elements. Some vertical motion of the shear-back coupler may be necessary under these conditions to allow the CEM system to be fully effective. As this CFR section does not allow yielding of the coupler carrier material, this requirement may interfere with the CEM design and is therefore not suggested as a practical design modification. In addition, the anti-climber characteristics provided by the drawbars and CEM design (as described in Section 7.2 of this report) will provide an equal level of override prevention required by this regulation. **Thus, a waiver for 49 CFR 238.207 will be requested.**

7.4. 49 CFR 238.209 Forward-Facing End Structure of Locomotives

Caltrain will require compliance with 49 CFR 238.209 in the vehicle specification. However, the requirement in 238.209 for a ½" thick (or equivalent) end sheet may not be met with the current European designs. This is still under review. While this would be a relatively simple modification to an existing design, close attention must be paid not to alter the performance of the CEM system, and care must be taken not to increase the weight of the EMU beyond acceptable levels. If such an alteration is found to negatively affect CEM performance during the procurement, a waiver will be sought, providing assurance of intrusion prevention can be demonstrated.

This regulation is currently undergoing revision by the FRA, to allow an alternate method of proving the strength of the end structure of the locomotive or cab car. This is further discussed in Sections 7.5 and 7.6 of this report, where it is most applicable.

7.5. 49 CFR 238.211 Collision Posts

Collision posts are required at both ends of every car body, per 49 CFR 238.211. This section is very prescriptive in that it provides the basic physical features of the posts and the static loads that it must react. Current European EMU designs do not meet this requirement, but do provide an end structure that provides at least equal protection in frontal impacts, whether it be train-to-train or grade crossing train-to-truck. **As currently written, a waiver for 49 CFR 238.211 will be requested.**

The FRA is currently revising this section of the CFR and it is likely that the revision will include an alternate method of proving the cab-end collision post (and corner post) compliance. Current EN15227-compliant cab designs can withstand an impact with the steel coil, as originally proposed by the FRA. They should be able to meet the revised requirements for the proxy object cart test, as the impact energy is virtually the same. If the revision to the regulation is made, the EMU specification will require compliance via this method, including verification of final design, and the waiver will not be required.

In addition to train-to-train collisions, which have already been discussed in Section 7.1 of this report, the end frame must protect against impacts with large obstacles, like highway trucks, at grade crossings. Two scenarios were examined in the Caltrain team analysis; collision with a large deformable truck per EN 15227 and collision with a steel coil on a flatbed trailer per the proposed 49 CFR 238 Appendix F. The FRA-compliant cab car and the EN15227-compliant EMU perform favorably and similarly in grade crossing collisions.

In the event that the expected revision to 49 CFR 238 is not released and a waiver is required, the Caltrain EMU specification will include the following requirements to address the cab-end collision post requirement:

- All items listed under Sections 7.1 – 7.4 of this report (49 CFR 238 sections 203, 205, and 207)
- Compliance with the FRA collision post “proxy object cart” impact requirement currently proposed for 49 CFR 238.205 Appendix F

49 CFR 238.211 also requires collision posts at the rear of each car, or each end of a semi-permanently coupled multiple unit. Thus, the rear end of the power car and both ends of the intermediate cars must also be equipped with collision posts. Current European designs do not provide structure that would meet this requirement. However, 238.211 (c) (1) states that collision posts may not be required if: “The railroad submits to the FRA Associate Administrator for Safety under the procedures specified in §238.21 a documented engineering analysis establishing that the articulated connection is capable of preventing

disengagement and telescoping to the same extent as equipment satisfying the anti-climbing and collision post requirements contained in this subpart and the FRA finds the analysis persuasive." It is expected that the current designs combining anti-telescoping connections and CEM will provide a convincing argument to the FRA. However, the specification will require the car builder to submit the final design to support that argument, showing:

- All items listed under Sections 7.1 – 7.4 of this report (49 CFR 238 sections 203, 205, and 207)
- Precisely how the drawbar and energy absorbing anticlimbers work to keep the two bodies at the intermediate connection safely connected as they come into contact with each other

7.6. 49 CFR 238.213 Corner Posts

Corner posts are required at both ends of every car body, per 49 CFR 238.213. See the explanation for 49 CFR 238.211 in regards to forward facing corner post. **As currently written, a waiver for 49 CFR 238.213 will be requested.** If the proposed revision to the regulation is made, the EMU specification will require compliance via this method, including verification of final design, and the waiver will not be required for the cab-end corner posts.

In the event a waiver is required, the Caltrain EMU specification will include the following requirements to address the cab-end corner post requirement:

- All items listed under Section 7.1 – 7.5 of this report (49 CFR 238 sections 203 - 211)
- Compliance with the FRA corner post "proxy object cart" impact requirement currently proposed for 49 CFR 238.205 Appendix F

No relief for rear corner posts is provided for drawbar-connected partially articulated cars. It is not likely that the corner post at the intermediate connection of an existing European EMU was designed to meet the regulation, as EN12663 requires reaction of loads that are lower than 49 CFR 238.213 and only oriented in the longitudinal direction. As previously discussed, intermediate car-to-car connections are well controlled in a collision due to the drawbar connection, the controlled crushing of CEM elements, and ultimately a rigid frame protecting the passenger compartment, which is the objective of this requirement. **Thus, a waiver for 49 CFR 238.213 will be requested for non-cab ends.**

Figure 67 shows the post-collision position of the rear of the EMU cab car and the front of the second car, after a 25-mph impact with a locomotive. The drawbar prevents override and bypass, and the two structures come together without compromising occupied space. Since the drawbar and the anticlimber/absorbers keep the two cars connected and aligned, there is no need to protect against impacts with other objects. This arrangement provides a level of protection from impacts that is, at a minimum, equivalent to the non-cab end frame requirement of 49 CFR 238.211 and 213. Note that the converging lines indicate that the finite element model of the trailing car was simplified through the use of beam elements based on the assumption that similarity between the two bodies would yield equally similar results.

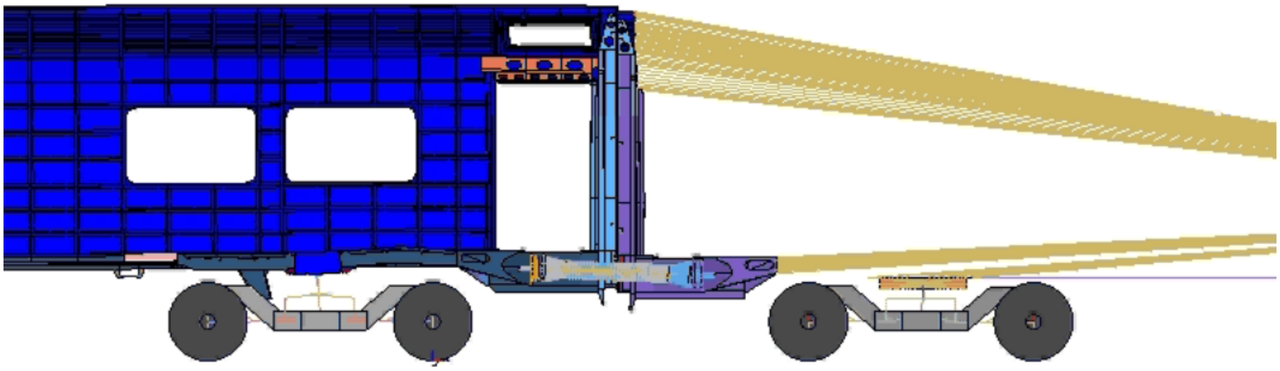


Figure 67 - EMU Intermediate Connections in a Train-to-Train Collision

EN 12663 requires a corner post that can resist loads that do not equal 29 CFR 238.213 loads in location, orientation, or magnitude. The objective is the same. First, to provide resistance to raking loads above the vehicle floor, and second to provide some protection against overriding. The EMU relies on the drawbar connection and anticlimber/energy absorbers to provide the primary resistance to overriding, which justifies the lower design load for the corner post base. Raking, caused by striking a piece of lading that might have gotten loose on a freight car on an adjacent track is addressed via placement of over-dimensioned lading detectors at strategic locations.

Since a waiver for rear/intermediate corner posts is required, the Caltrain EMU specification will include the following requirements as mitigation to any associated risk:

- All items listed under Section 7.1 – 7.5 of this document (49 CFR 238 sections 203-211)
- Calculations showing the amount of deformation of the corner structure of the rail car when the static loads prescribed by 49 CFR 238.213 are applied does not compromise the occupied space

8. CONCLUSIONS

The following conclusions can be drawn from this study:

- It is possible to ensure that Caltrain’s overall system wide safety will not be compromised by operating European-style EMUs concurrently with existing FRA-compliant rolling stock. Safety is maintained, and even enhanced, via mitigation strategies integrated with equipment and operations that reduce the severity and frequency of possible hazardous situations. These mitigation strategies include, grade crossing improvements, positive train control provided by CBOSS, temporal separation of freight, revised operating and maintenance procedures, and a technical specification that requires demonstration of compliance with both EN15227 for crash energy management (CEM) designs, special measures presented in Section 7 of this report, and all sections of 49 CFR 238 with the following exceptions (for which waivers will be requested):
    - 49 CFR 238.203 Static End Strength
    - 49 CFR 238.205 Anti-Climbing Mechanism
    - 49 CFR 238.207 Link Between Coupling Mechanism and Car Body
    - 49 CFR 238.211 Collision Posts
    - 49 CFR 238.213 Corner Posts

- Both FRA-compliant cab cars and EN15227-compliant EMUs perform similarly in grade crossing collisions with small and large highway vehicles. Thus, any risk associated with a grade crossing collision is similar with either vehicle type. Caltrain is committed to continuing the grade crossing improvement program to reduce the number of incidents through all practicable means.

- Both FRA-compliant cab cars and EN15227-compliant EMUs perform similarly in train-to-train collisions, in that the consequences are catastrophic as closing speeds exceed 20 mph. Risk associated with a train-to-train collision is inherent with either vehicle type, and any combination of impacting trainsets. Incremental improvements in any design will only move the threshold impact speed up by single digits in mph. Thus, another means of avoiding collisions at these higher speeds must be implemented. Caltrain is committed to implementing a positive train control system to reduce the risk of train-to-train impacts at speeds above 20 mph. Operation at speeds below 20 mph (restricted speed) will be possible in situations where PTC is not active.

- Both FRA-compliant cab cars and EN15227-compliant EMUs perform similarly in post-derailment collisions with a fixed object, in that the estimated consequences are catastrophic at closing speeds above about 10 mph. Caltrain is committed to a vigilant infrastructure and rolling stock maintenance program to minimize the risk of derailment and possible post-derailment collision with fixed objects.

9. REFERENCE DOCUMENTS

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[4] Code of Federal Regulations, Title 49, Office of the Secretary of Transportation, Subtitle B--Other Regulations Relating to Transportation, 200-299 Federal Railroad Administration, 2009

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