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Federal Railroad Administration

Crashworthy Components Retrofit for F40 Locomotive

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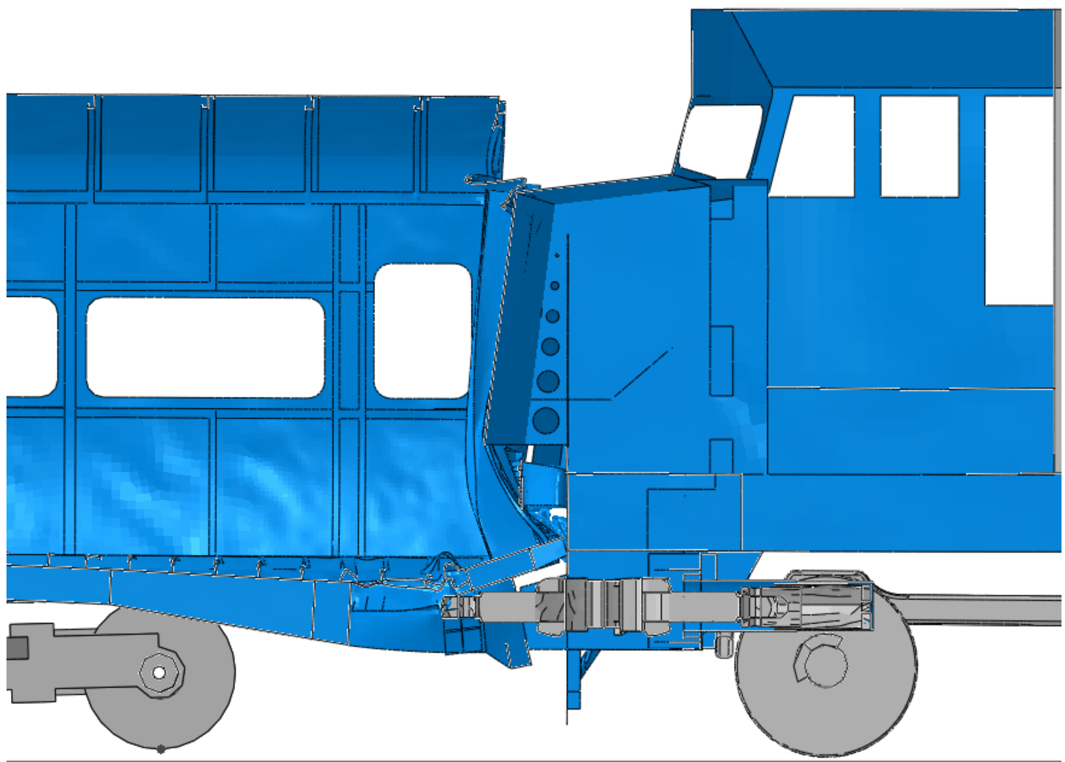
Washington, DC 20590



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13. ABSTRACT

The Federal Railroad Administration and the Volpe Center continue to evaluate new technologies for increasing the safety of passengers and operators in rail equipment. In recognition of the importance of override prevention in train-to-train collisions in which one of the vehicles is a locomotive, and in light of the success of crash energy management technologies in cab car-led passenger trains, the Volpe Center sought to evaluate the effectiveness of components that could be integrated into the end structure of a locomotive that are specifically designed to mitigate the effects of a collision and, in particular, to prevent override of one of the lead vehicles onto the other.

In a research program completed in 2012, detailed designs for two crashworthy components for a passenger locomotive—a push-back coupler and a deformable anti-climber—were developed, evaluated, and tested. Based on a successful full-scale rail impact test demonstration of component performance, the Volpe Center now wishes to retrofit the designs for these two components onto an F40 locomotive and perform a series of full-scale collision tests. The research described in this report develops and evaluates modifications required to retrofit the design for these two components onto the F40 locomotive.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

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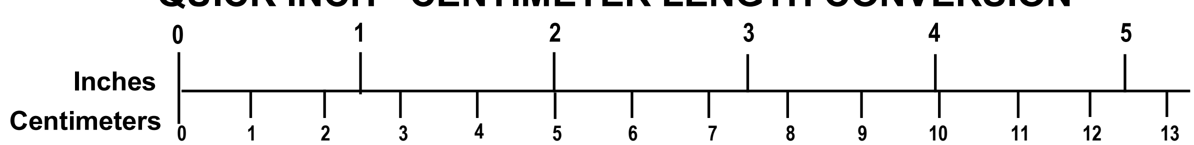
QUICK INCH - CENTIMETER LENGTH CONVERSION



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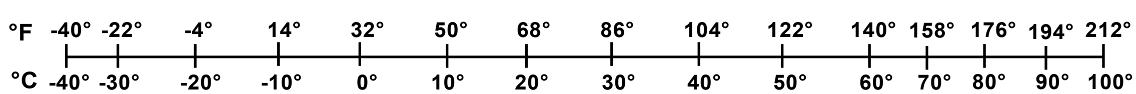

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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We would also like to thank the following individuals who supported this program: Luis Maal of FRA who facilitated our visit to TTC; Przemyslaw Rakoczy and others at TTCI who hosted our visit to TTC and answered a number of questions; Antony Jones of Voith Turbo, who answered a number of questions regarding the Voith push-back coupler that is included as part of the push-back coupler system. We appreciate the help of Trinity Rail, Bombardier, and EMD, who all provided drawings for use in the program.

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Executive Summary

In support of the Equipment Safety Research Program within the Federal Railroad Administration (FRA), the Volpe Center has been conducting research to improve structural crashworthiness of passenger rail cars and to improve occupant protection for rail car passengers. As a part of this work, crash energy management (CEM) strategies, in the form of crush zones incorporated at the ends of passenger cars, have been developed and tested with the aim of preserving the occupant volume in passenger cars.

In the event of a head-on collision between two trains, a considerable amount of energy must be dissipated. One of the potential consequences of such a collision is override of one of the leading vehicles onto the other. Because of their great longitudinal strength and stiffness, locomotives are particularly susceptible to override when they collide with another vehicle. The consequences of an override are often catastrophic.

Research has shown that the addition of a few structural features to the leading end of a locomotive can greatly reduce the propensity for override. In 2009, as a follow-up to the earlier program, FRA and the Volpe National Transportation Systems Center (Volpe) planned and funded a research program ("Locomotive Crashworthy Components" [1]) to develop, fabricate and test two crashworthy components for the forward end of a locomotive: a deformable anti-climber, and a push-back coupler. TIAX was selected as the prime contractor for this work and conducted the program under the guidance from Volpe.

In the 2009 program (completed in 2012), detailed designs for these components were developed, and the performance of each design was evaluated through large-deformation dynamic finite element (FE) analysis. Designs for two test articles that could be used to verify the performance of the component designs in full-scale tests were also developed. The two test articles were fabricated and dynamically tested by means of rail car impact to verify certain performance characteristics of the two components relative to specific requirements. The tests were successful in demonstrating the effectiveness of the two design concepts.

The FRA and Volpe are currently planning to conduct a number of vehicle-to-vehicle collision tests to further evaluate the merits of the locomotive crashworthy components that were developed in the 2009 program. These tests will be conducted at the Transportation Technology Center (TTC) in Pueblo, CO. It is anticipated that the locomotive that will be modified for use in such tests is the F40 locomotive manufactured by EMD. The previously-developed crashworthy components were designed for retrofit into an MotivePower MP40 locomotive. Due to differences in the design of these two locomotives, the design for the crashworthy components need to be modified so that it is suitable for retrofit into an F40 locomotive, more specifically, an F40 locomotive that currently is located at the TTC and is available for use in upcoming tests.

The objective of the research program described in this report has been to develop designs for retrofit of the crashworthy components into the end of an F40 locomotive. To meet this objective, TIAX and its subcontractor Canarail completed a number of activities aimed at: (1) identifying the required modifications to the design, (2) creating CAD models of the modified designs; (3) creating FE models of the modified locomotive as well as for several other vehicles into which it may collide; (4) evaluating the designs through FE simulations of a number of collision scenarios; and (5) producing a drawing package for both fabrication of the modified components, modifications to the locomotive, and installation of the components on the modified locomotive.

Required modifications to the design were identified through review of F40 locomotive drawings and a visit to the TTC in Pueblo, CO to inspect the F40 test vehicle. A Bombardier model M1 cab car, which is also planned for use in testing, was also inspected during this visit.

Three-dimensional CAD models of both the modified and conventional locomotives were constructed using the SolidWorks CAD program. These models were used to define the geometry of the FE meshes for these vehicles. In addition, FE models of an M1 cab car were created and an existing half-length model of a Trinity Rail center beam flat car was modified to be full-length. These meshes formed the basis of FE models for simulation of four collision scenarios. For each of the vehicle-to-vehicle collision scenarios, two additional offset cases were also analyzed:

The results of the FE analysis indicate that both components behave effectively in all of the collision scenarios. Required energy absorption levels were not met in only one scenario — a collision between a modified locomotive and a cab car for which the cab car was lowered by 3 inches and shifted laterally by 3 inches. For this case, the energy absorption of the deformable anti-climber reached only 440 ft-kips before the draft sill of the cab car began to buckle, and once the buckling commences, most of the deformation occurs in the cab car. In spite of this low energy absorption value, the total energy absorption for this scenario was still over 2 million ft-lbf, and the end frames of the modified locomotive and the cab car engage extensively, indicating that override of one onto the other is unlikely.

Following the successful FE-based evaluation of the modified design, a drawing package was produced by Canarail to guide fabrication and installation of the retrofit design. This design was reviewed by TIAX's metal fabrication specialist and chief CAD designer. A few modifications were identified in this review. The design was also shared with TTCI, who will be responsible for completing the retrofit.

1. Introduction

The Federal Railroad Administration (FRA), with assistance from the Volpe National Transportation Systems Center (Volpe), has been engaged in active research aimed at improving the crashworthiness of rail vehicles for many years. Much of this work has focused on mitigating the consequences of train-to-train collisions.

1.1 Background

In the event of a head-on collision between two trains, a considerable amount of energy must be dissipated. One of the potential consequences of such a collision is override of one of the leading vehicles onto the other. Because of their great longitudinal strength and stiffness, locomotives are particularly susceptible to override when they collide with another vehicle. The consequences of an override are often catastrophic.

Accident investigations and other forms of research have shown that anti-climbing systems built into the ends of conventional locomotives are generally ineffective in preventing override. Impact between colliding couplers can induce dynamic vertical forces that cause one of the colliding vehicles to pitch significantly.

Research has further shown that conventional anti-climbing structures can deform on impact and form a ramp, increasing the likelihood of override [2]. As they crush longitudinally, conventional anti-climbers lose their vertical load-carrying capacity due to the substantial fracture that occurs as the anti-climber crushes. The longitudinal crush of the anti-climber causes fracture in the webs behind the face of the anti-climber. These fractured webs can still resist a longitudinal compression load, but can no longer transmit a vertical shear load. This loss of vertical load-carrying capacity in conventional anti-climbers often leads to ramp formation, which promotes override. Such behavior was exhibited in a head-on collision that occurred in West Eola, Illinois on January 20, 1993. As seen in Figure 1, this accident resulted in one locomotive (right side of photo) overriding the other, crushing the operator's cab. The photograph shows the overriding locomotive lifted off of its lead truck. In order to be effective, an anti-climber must engage the end structures of opposing equipment and provide sufficient vertical load capacity to prevent such override.

Figure 1. West Eola, Illinois head-on collision, January 20, 1993

Research has also shown that the addition of a few structural features to the leading end of a locomotive can greatly reduce the propensity for override [3]. These features include:

- Push-back or breakaway couplers that allow the ends of the vehicles to interact prior to the build-up of large forces and moments that might lead to significant pitching of the vehicles with respect to one another.
- Interlocking features and vertical strength characteristics that resist relative vertical motion of one vehicle with respect to the other so as to prevent the formation of a ramp.
- Crushable zones that absorb collision energy so as to prevent uncontrolled deformation of interlocking features that might cause formation of a ramp.

Structural features such as these that are specifically put in place to mitigate the effects of a collision are common in rail vehicles designed according to the principles of crash energy management (CEM). CEM is a design strategy aimed at increasing occupant survivability during a collision, and is based on the notion that the energy of a collision can be dissipated in a controlled manner through the use of crush zones and other structural features.

CEM systems for passenger trains have been widely employed in Europe. In the U.S., CEM systems are just now beginning to be developed. Beginning in about 2000, FRA and Volpe initiated a series of research programs aimed at developing a CEM system for a passenger train. These activities culminated in a full-scale collision test between a cab-car-led passenger train outfitted with a CEM system, traveling at 34 mph, and a standing, conventional-locomotive-led train. This test, conducted in March 2006, was very successful and clearly demonstrated the benefits of CEM design. Not only did the CEM train dissipate the energy of the collision through controlled deformation of crush zones throughout the length of the train, but the passenger train and the locomotive-led train both stayed on the track. This was in stark contrast to the results of a similar test of conventional equipment, where the cab car overrode the locomotive. Figure 2 illustrates the outcomes of these two collisions.

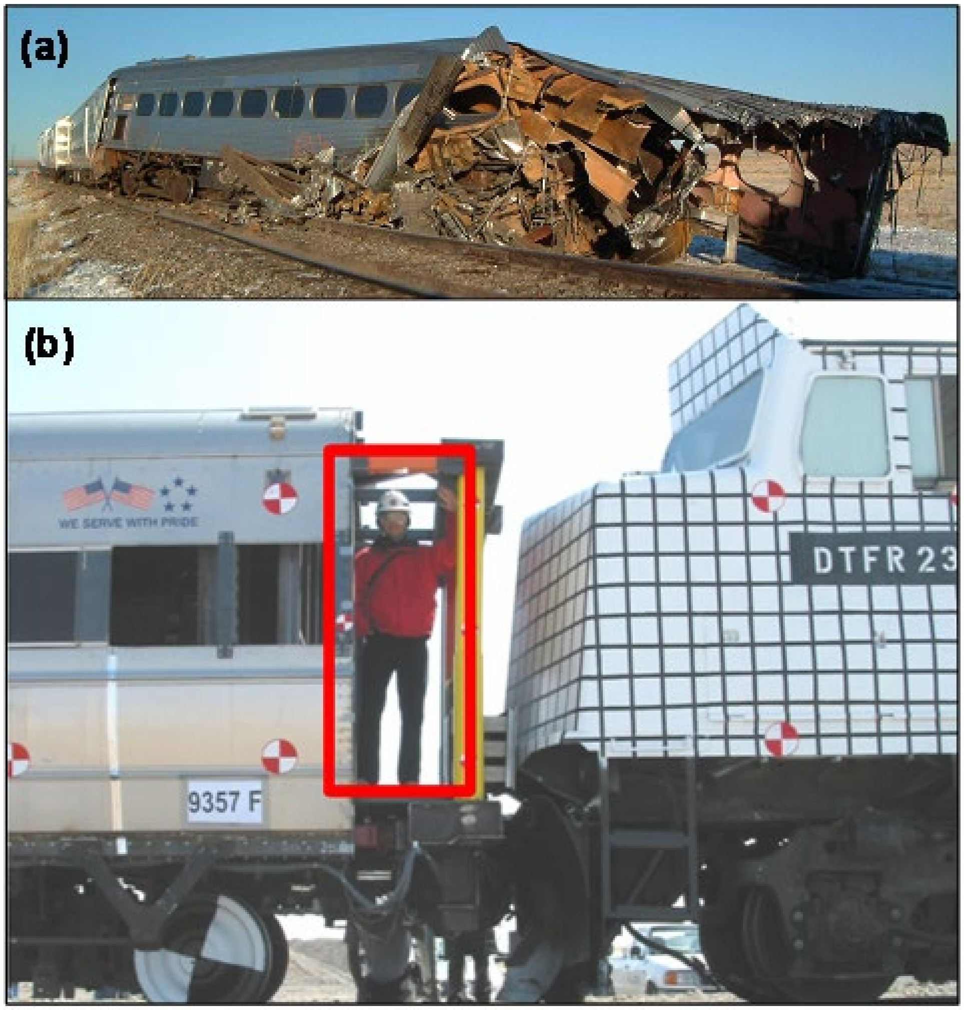


Figure 2. A comparison of the outcomes of full-scale collision tests for: (a) a conventional passenger train and (b) a CEM-based passenger train

The successful outcome of the CEM train-to-train collision test has helped to convince passenger rail operators that lives can be saved by employing crashworthiness features in their trains. The Southern California Regional Rail Authority (SCRRA) has procured a number of CEM-equipped vehicles for its Metrolink fleet.

With the success of the passenger train CEM system, FRA and Volpe are revisiting locomotive crashworthiness. A research program [4] conducted by Arthur D. Little (now TIAX) examined the feasibility of incorporating anti-climbing systems in cab cars and locomotives. As part of this program, design concepts for locomotive override protection were developed and evaluated through analysis. Concepts for crashworthy components that were identified included: PBCs, DACs, and crush zones built into the forward end of the locomotive underframe.

As a follow-up to the earlier program, in 2009, FRA and Volpe planned and funded a research program ("Locomotive Crashworthy Components" [1]) to develop, fabricate, and test two crashworthy components for the forward end of a locomotive: a DAC, and a PBC. TIAX was selected as the prime contractor for this work and conducted the program under the guidance of the Volpe Center.

In this program, detailed designs for these components were developed, and the performance of each design was evaluated through large-deformation dynamic finite element analysis (FEA). Designs for two test articles that could be used to verify the performance of the component designs in full-scale tests were also developed. The two test articles were fabricated and dynamically tested by means of rail car impact to verify certain performance characteristics of the two components relative to specific requirements. The tests were successful in demonstrating the effectiveness of the two design concepts. Test results were consistent with FEA model predictions in terms of energy absorption capacity, force-displacement behavior, and modes of deformation.

1.2 Objectives

The objectives of the locomotive crashworthiness research described in this report were to re-design the push-back coupler (PBC) and deformable anti-climber (DAC) for retrofit to an F40 locomotive, generate CAD then FE models of several vehicles involved in collision scenarios that demonstrate the crashworthy components provide crashworthiness compatibility with a range of equipment and exhibits increased crashworthiness over conventional equipment, then prepare fabrication and installation drawings for the retrofit.

1.3 Overall Approach

Based on the successful outcome of the Locomotive Crashworthy Components program, FRA wished to continue to evaluate the apparent benefits of PBCs and DACs in full-scale vehicle collision tests. The locomotive selected for these tests was the F40, manufactured by EMD. Four tests were considered:

- Modified F40 into a rigid wall
- Modified F40 into a conventional F40
- Modified F40 into a conventional cab car
- Modified F40 into a conventional freight car.

Because the end structure of the F40 locomotive differed from that of the MP40 locomotive, the design of each of the components required modification. In addition, the design of the end structure of the F40 locomotive required modification to accommodate these components, as did the MP40 locomotive for which the components were originally designed.

TIAX's work plan to evaluate the F40 retrofit design featured several activities. Researchers first reviewed drawings of the F40 locomotive, and then inspected an F40 locomotive located at the TTC in Pueblo, CO, that was a candidate for retrofitting. They documented the current status of the end structure of the locomotive, which had been modified to meet S-580 standards, and identified differences between the actual structure and what was specified in the drawings supplied.

With this information in hand, the research team developed a CAD model for an un-modified F40 locomotive consistent with the test vehicle inspection at the TTC. Starting with this model, a model for an F40 locomotive modified to include the two crashworthy components was developed.

Based on the CAD models, drawings, and other available information, the team constructed FE models of both vehicles. It also constructed an FE model for an M1 cab car (which was also inspected during the visit to the TTC) and modified an existing FE model for a Trinity Rail freight car.

Researchers then used these models to simulate four collision scenarios consistent with the planned collision tests described above. For each vehicle-to-vehicle scenario, they evaluated a baseline case, with the vehicles aligned, plus two offset cases, with an initial 3-inch vehicle offset in both the vertical and lateral directions.

Finally, once the design of the modified system was completed and had been verified through FEA analysis, the team prepared fabrication and installation drawings as well as construction sequence documents. It then had these drawings reviewed to help identify any potential fabrication or installation issues.

1.4 Scope

This report details the design and evaluation of the locomotive crashworthy components for the F40 locomotive. This includes the re-design of the components for an F40 locomotive, generation of CAD models, construction of FE models of the vehicles, and evaluation of the FE analyses of the vehicles in several collision scenarios. Fabrication and installation drawings are also provided.

1.5 Organization of the Report

Section 2 describes the measurement of existing vehicles, two locomotives and a cab car.

Section 3 presents the design requirements for the crashworthy components, including performance, geometric, operational, and fabrication requirements.

Section 4 details the modification of the retrofit designs and the finite element models developed for analysis.

Section 5 describes the evaluation of the retrofit designs through extensive finite element analyses.

Section 6 details the drawings and construction sequence.

Section 7 provides a summary and conclusions.

2. Measurement of Existing Vehicles

The objective of the first technical task of the program was to document differences between the F40 locomotive test vehicle (which had previously been modified to satisfy S-580 requirements) and an un-modified F40 locomotive as specified in the available mechanical drawings.

A set of drawings for the F40 locomotive was provided to TIAX by the Volpe Center. It was later determined that the drawing package provided was for a model F40-PHM-2 locomotive. The test locomotive at the TTC (234) is actually a model F40-PHR locomotive. The Volpe Center later coordinated the procurement of additional drawings for the F40-PHM-2 locomotive from EMD.

In November 2014, a visit to the TTC in Pueblo, CO, was arranged by the Volpe Center for the purpose of inspecting the F40 test locomotive. Six individuals—two from TIAX, two from TIAX's subcontractor Canarail, and two from the Volpe Center—participated in this visit. F40 drawings were reviewed by TIAX and Canarail prior to the trip to the TTC.

At the TTC, researchers documented, through measurements and photographs, the test vehicle end structure geometry, and identified differences between the test vehicle end structure and what was specified in the drawings. They also sought to identify structures that may have interfered with component integration.

The team inspected three vehicles at the TTC: Locomotive 234 (see Figure 3), the planned F40 test vehicle, modified to be S-580-compliant; Locomotive 202, an un-modified F40 locomotive; and car 9324, an M1 cab car damaged in a fire and under consideration for use in a locomotive-into-cab car collision test.

2.1 Locomotive 234

Locomotive 234, an EMD model F40-PHR, was built as Amtrak 234, serial number 777001-5. It is DC-powered, with 40-inch wheels (see Figure 3).

Figure 3. Locomotive 234: Left—prior to S-580 modifications, in operation for Amtrak; right—current state as the TTC test vehicle, following S-580 modifications

The unit was modified in 2001 to S-580 compliance by TTCI. The train-to-train test report indicated that only the short hood and collision posts were replaced [5]. It was not clear what other modifications may have occurred in between. It had been used in train-to-train tests and in several other impact tests.

The end plate of unit 234 had been repaired, including new stiffening angles (see Figure 4 and Figure 5). A repair is clearly visible in Figure 5, looking up from underneath the apron top plate where it joins one of the horizontal gusset plates.

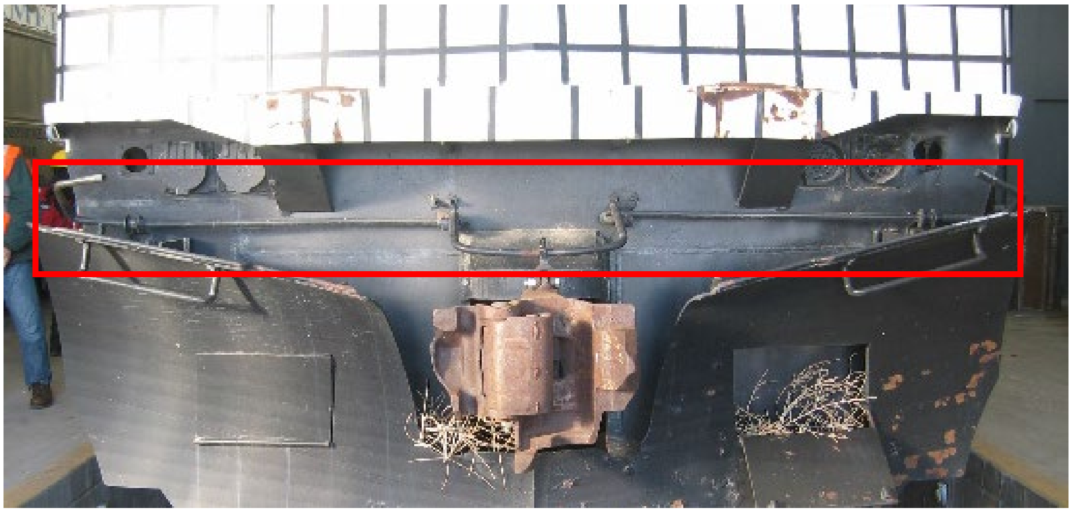


Figure 4. Stiffening angles (gusset plates) of unit 234 that have been replaced

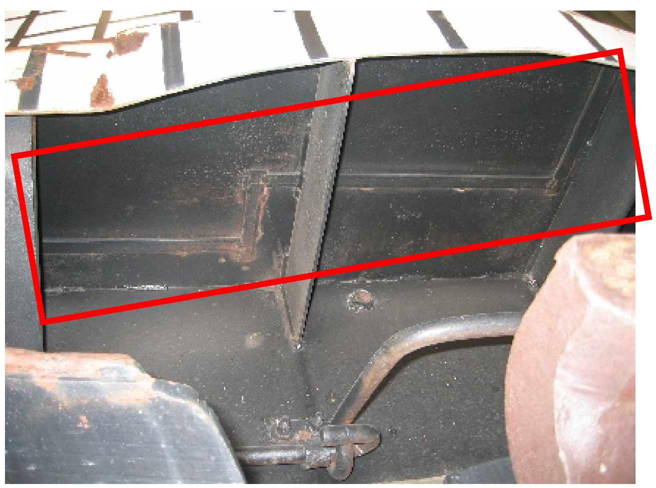


Figure 5. Repaired apron top plate of unit 234

2.2 Locomotive 202

Unit 202, which was also inspected, is an EMD model F40-PH, which most obviously differs in wheel diameter (42 inches) and current type (AC). An inspection of this vehicle revealed no obvious structural modifications. The plates that form the front of the short hood appeared to be thinner (3/16 inch) than those of the S-580-modified F40, and the collision posts, also thinner (0.25 inch), were not welded to the short hood.

Figure 6. Un-modified (to S-580 requirements) EMD model F40-PH locomotive unit 202 at the TTC

2.3 M1 Cab Car

A Bombardier model M1 cab car that had operated as Long Island Rail Road unit 9324 was also inspected at the TTC. This unit, depicted in Figure 7, which may be used in a future locomotive-to-cab car collision test, had been damaged in a fire.

Figure 7. Bombardier model M1 cab car unit 9324, photographed at the TTC

3. Design Requirements

Design requirements for a platform-style locomotive with increased crashworthiness due to the incorporation of a PBC and DAC were defined as part of the 2009 research program [1]. They are listed here for reference. Minor changes to the requirements have been made to reflect modifications to the collision scenarios and are indicated.

These requirements govern the development of designs for PBC and DAC components, and include collision scenarios for evaluating their behavior in a collision with another vehicle.

The design requirements include performance, geometric, operational, and fabrication requirements. The energy absorption requirements and many of the other crashworthiness specifications are derived from experience gained in other crashworthiness programs. Most of the strength requirements and some of the crashworthiness specifications are derived from the APTA [6] and AAR [7] standards. All requirements are consistent with CFR 49 Part 229 [8], APTA SS-C&S-034-99, Rev 2 [6], and APTA RP-C&S-019-11 [9]. Figure 8 shows the DAC and PBC system designed from the requirements found in the following section.

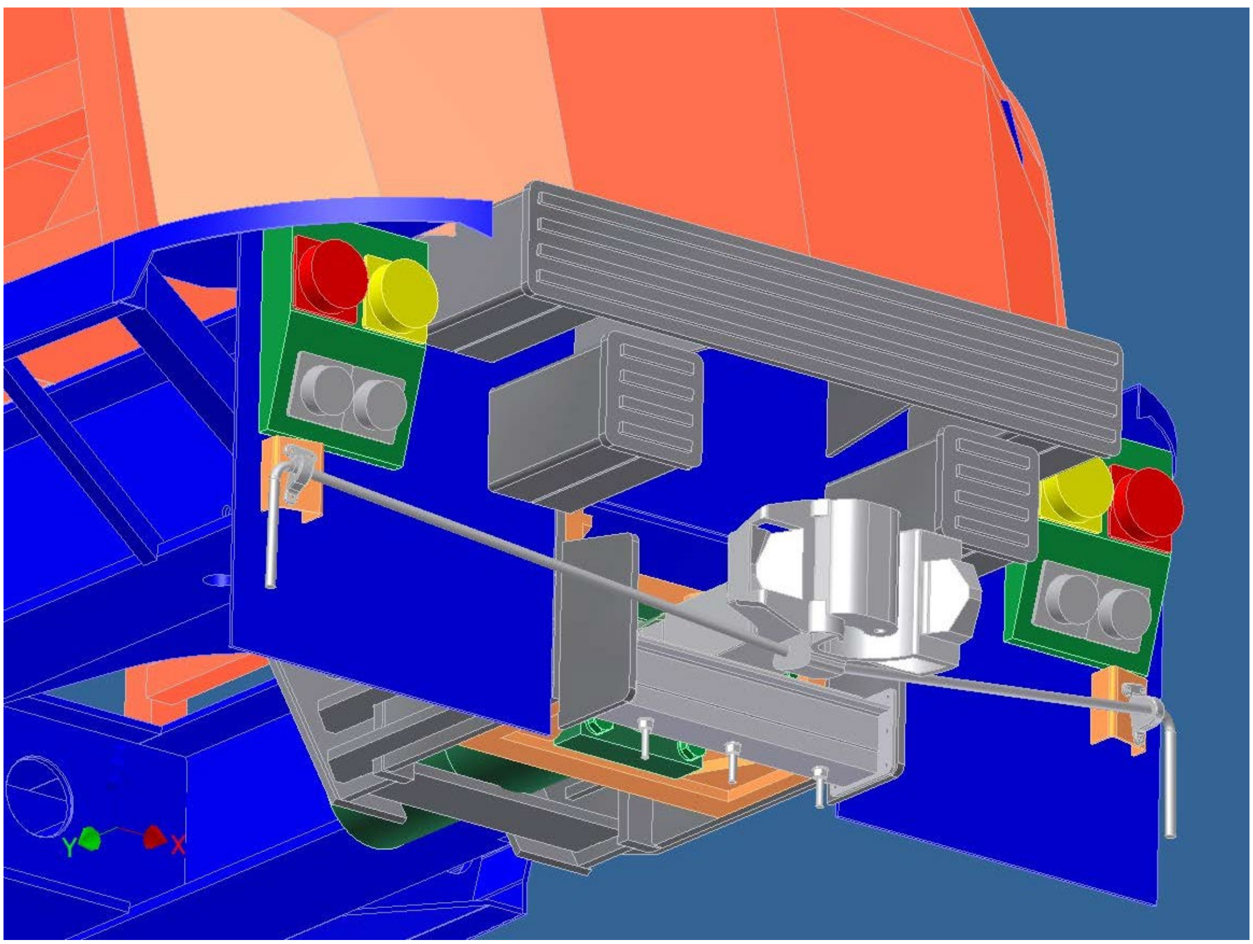


Figure 8. View of the DAC and PBC system

3.1 Performance Requirements

3.1.1 Push-back Coupler

- Push-back enables end frames of colliding equipment to engage.
- Stroke: The PBC must be capable of pushing back with enough stroke to accommodate and capture conventional locomotive, cab car and freight car couplers. The minimum will be based on interaction with cab and freight cars, and the maximum based on open space behind draft pocket.
- Trigger mechanism: shear bolt or deformation tube arrangement
- Trigger load: minimum 600,000 lbf/maximum 800,000 lbf
- Energy absorption: must absorb energy in a controlled manner while pushing back; minimum 600,000 ft-lbf (based on stroke and load characteristics)
- Support structure: no permanent deformation prior to exhaustion of PBC stroke; crippling load of support structure must not be exceeded in a 12 mph impact into another consist
- Torsional resistance: minimum 150,000 ft-lbf prior to push-back and after exhaustion of push-back function
- Retention: must be strong enough to support a draft load of 150,000 lbf at any time during push-back and after exhaustion of push-back function
- No material failure (material separation)

3.1.2 Deformable Anti-climber

- Stroke: minimum 10 inches (based on operational requirements, geometric requirements, and interaction with cab and freight cars)
- Trigger mechanism: plastic deformation/progressive buckling of energy absorbers
- Energy absorption: minimum 600,000 ft-lbf (based on stroke and load characteristics)
- Vertical strength: 100,000 lbf in both un-deformed and fully-deformed configurations
- Support structure: strong enough to support crush load without failing or undergoing large plastic deformation; crippling load of support structure must not be exceeded in a 12 mph impact into another consist.
- No material failure (no separation); highly localized material failure will be permitted so long as it does not affect the repeatability of anti-climber crush behavior.

3.1.3 Collision Scenarios

A locomotive design featuring crashworthy components would necessarily be placed in service along with conventional equipment. For this reason, the consequences of four different collision scenarios must be evaluated:

1. Modified locomotive into rigid wall (essentially equivalent to modified locomotive into modified locomotive)
2. Modified locomotive to conventional locomotive
3. Modified locomotive to cab car
4. Modified locomotive to freight car.

In these scenarios, the modified locomotive is moving at a prescribed initial speed and the second vehicle is standing.

The collision speed for each scenario will be defined so as to exhaust the stroke of both the DAC and PBC energy absorption systems and initiate loading of the locomotive underframe. Each scenario will be evaluated for three conditions:

1. Vehicles perfectly aligned.
2. The standing vehicle offset upward by 3 inches and laterally by 3 inches with respect to the modified locomotive.
3. The standing vehicle offset downward by 3 inches and laterally by 3 inches with respect to the modified locomotive.

Performance in each scenario will be evaluated through large-deformation dynamic finite element analysis (FEA).

The following criteria shall be used to evaluate satisfaction of the requirements relative to the collision scenarios:

- No override of one vehicle onto another.
- No formation of a ramp that might eventually lead to override.
- No uncontrolled deformation in modified locomotive
- No uncontrolled deformation in conventional vehicles
- A best-fit straight line approximation of the force/crush data shall exhibit a positive slope until the crush for the crashworthy components is exhausted and the underframe begins to crush.
- The strength of the underframe shall be at least 50 percent higher than the crush strength of the combined DAC/PBC system.
- The underframe must be strong enough to support the loads on the DAC and PBC without undergoing large deformation.

3.2 Geometric Requirements

3.2.1 Push-back Coupler

- Cannot interfere with existing locomotive structures during and following push-back to its complete stroke.

3.2.2 Deformable Anti-climber

- Width: must extend laterally, at a minimum, to the approximate 1/3 points across the width of the end of the locomotive; must also extend laterally to the main longitudinal beams of the locomotive.
- Depth: center must extend to within 4 inches of the pulling face of the coupler with the draft gear fully compressed and must extend no less than 10 inches from the locomotive front plate for its required width.
- Cannot interfere with other equipment on the locomotive, unless it is agreed that such equipment can be easily re-routed.

3.3 Operational Requirements

- Low-speed coupling: The PBC system must be able to withstand a hard coupling between two locomotives at 5 mph without triggering the push-back system.
- Curving: The components of the locomotive shall not interfere with nominally identical vehicles operating on curves up to 23 degrees.

3.4 Fabrication Requirements

3.4.1 General

- The design should utilize materials and fabrication methods that a typical metal fabrication company could use.

3.4.2 Materials

- The materials of construction for the primary structure and the energy absorbing elements shall be either high-strength, low-alloy (also known as low-alloy, high-tensile) or austenitic stainless steels commonly used in the fabrication of modern railway vehicles for operation in North America. Aluminum honeycomb may be used for energy absorbers.

3.4.3 Construction Methods

- All primary structural members shall be welded in accordance with AWS D1.1. Bolting may be used for the PBC trigger mechanism.

3.4.4 Overall Vehicle Integration

- The PBC and DAC components shall be designed so that they can be integrated onto an existing passenger locomotive.

4. Modify Retrofit Designs

TIAX modified the design of the PBC and DAC elements and modified the structure of the F40 locomotive to accommodate retrofit of these elements into its end frame. In addition, TIAX used the available information, including existing FE models, drawings, CAD models, and photographs and measurements from the TTC visit, to develop FE models for each of the four vehicles that were simulated in the various collision scenarios.

4.1 Schematics of Retrofit Designs

Starting with the design that was developed in the recent program for retrofitting the crashworthy components onto an MP40 locomotive, TIAX subcontractor Canarail developed designs for retrofit of these components onto the F40 test vehicle that was inspected at the TTC. With the aid of drawings and the information gathered during the inspection, Canarail first developed a CAD model of the S-580-compliant F40 locomotive using SolidWorks [10]. They then modified the end structure of the F40 locomotive so as to integrate the two components, ensure that the loads that were transmitted through them during crushing could be supported, and to ensure that there would not be geometric interference during crush of the anti-climber element or actuation of the PBC.

Key considerations for the design modifications included two major differences between the end structures of the MP40 locomotive and the F40 locomotive, as illustrated in Figure 9, namely:

- On the MP40 locomotive, the front ends of the collision posts were flush with the end plate; on the F40 locomotive, the front ends of the collision posts extended forward of the end plate (to which the DAC is mounted) by approximately 10.6 inches.
- On the MP40 locomotive, the distance between the end plate and the center of the forward bolster was about 126 inches; on the F40 locomotive, this distance was only 114 inches. For this reason, the travel of the deformation tube of the PBC extended over the transom bar located at the front of the forward truck, and came close to interfering with the traction motor mounted on the truck axle.

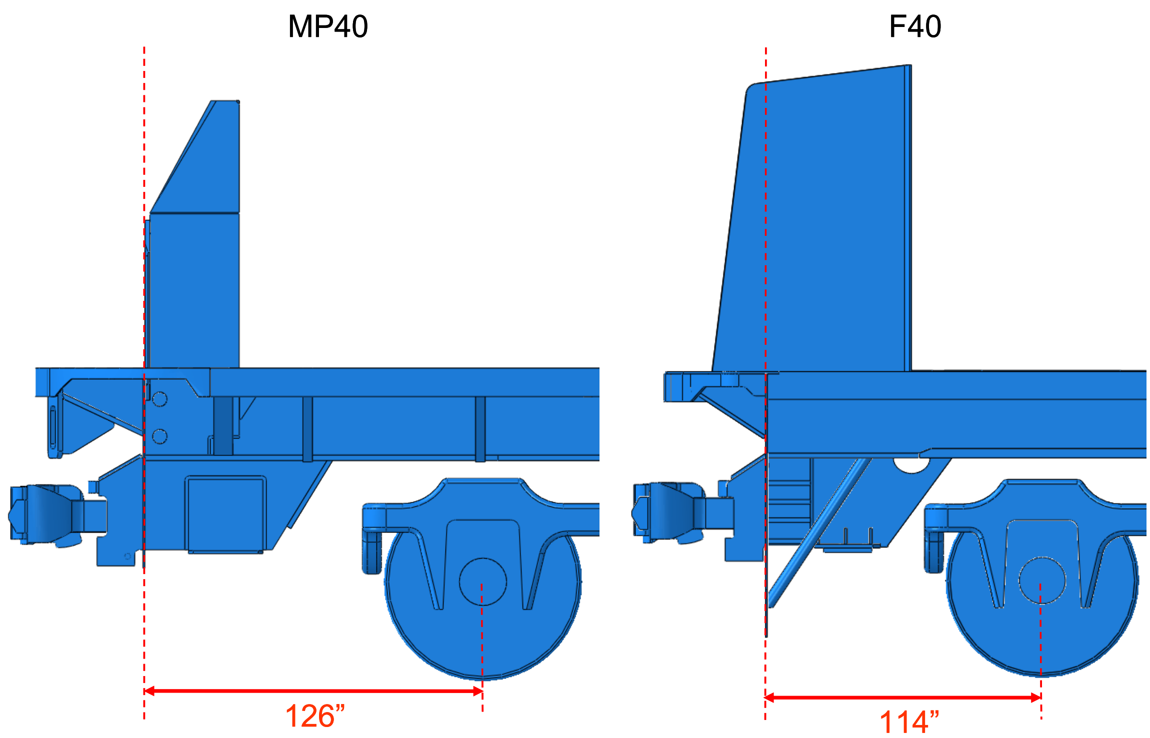


Figure 9. Side views from respective CAD models (with many details removed) comparing MP40 and F40 locomotive end structures

4.1.1 Un-modified F40

A 3-dimensional CAD model of the un-modified F40 was constructed at Canarail, using information provided in drawings and collected during the inspection. The model was built to be consistent with Locomotive 234 and, as such, included modifications to make it S-580 compliant. Note that the model was later updated using thickness information obtained from EMD. These updates mostly were with respect to the thickness of floor plates inside the short hood, as illustrated in Figure 10. All dimensions were checked against measured data and available drawings. A view of the underside of the locomotive end frame is shown in Figure 11.

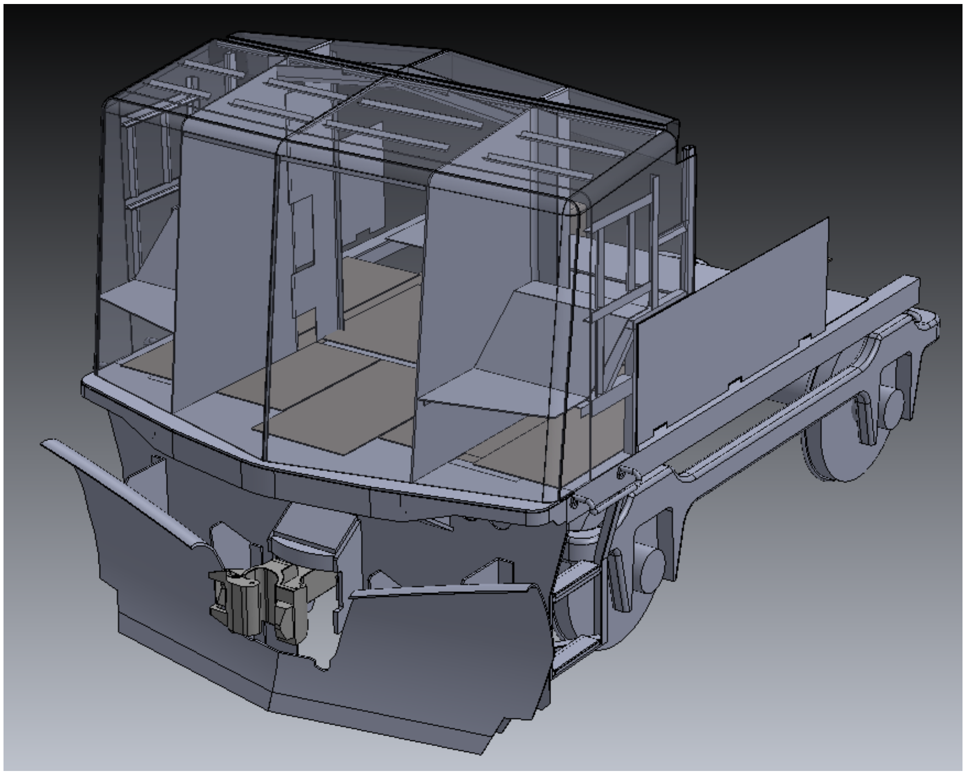


Figure 10. CAD model of a conventional F40 locomotive (modified to be S-580 compliant)

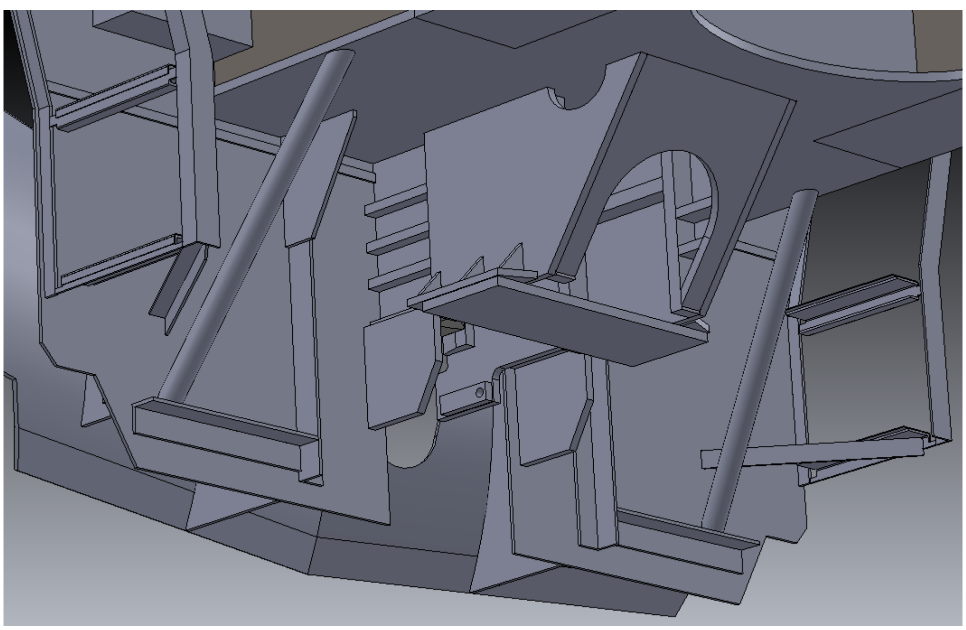


Figure 11. A view showing the underside of the conventional F40 endframe

4.1.2 Modified F40

Canarail developed a CAD model constructed to represent a design for an F40 locomotive that had been modified to include the two crashworthy components. A preliminary version of the model was first developed and reviewed with the Volpe Center on February 26, 2015. A revised version of the model was then constructed. This model, shown in Figure 12, included significant changes to the endframe of the locomotive, illustrated in Figure 13 through Figure 17, and described below.

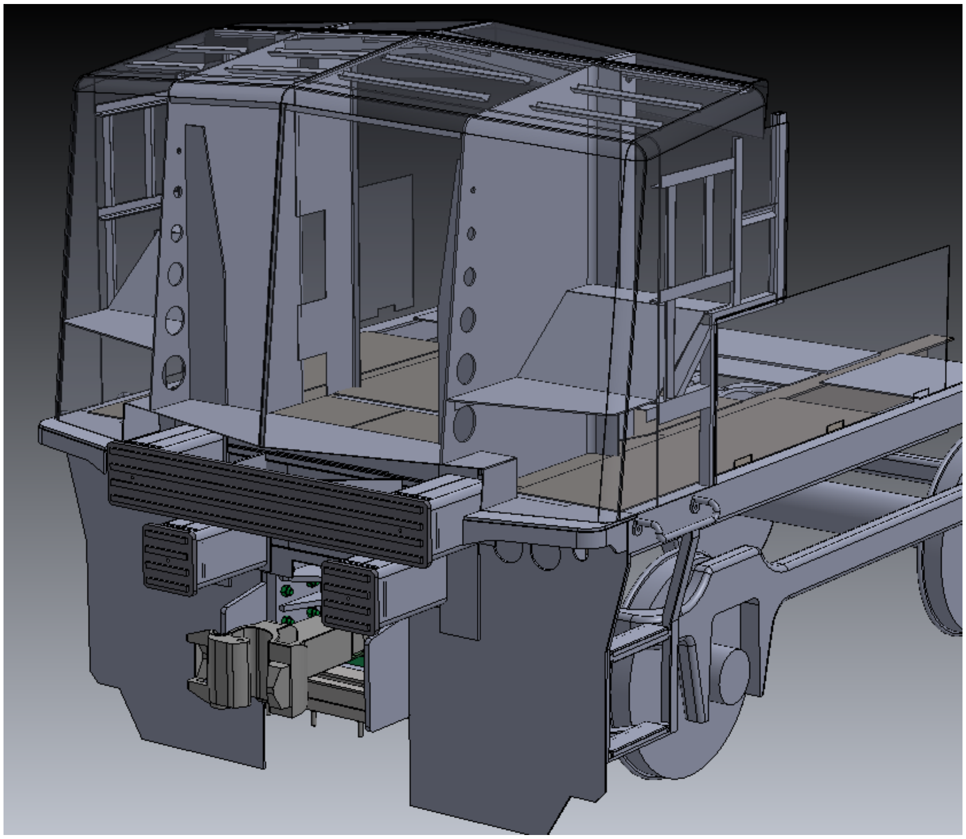
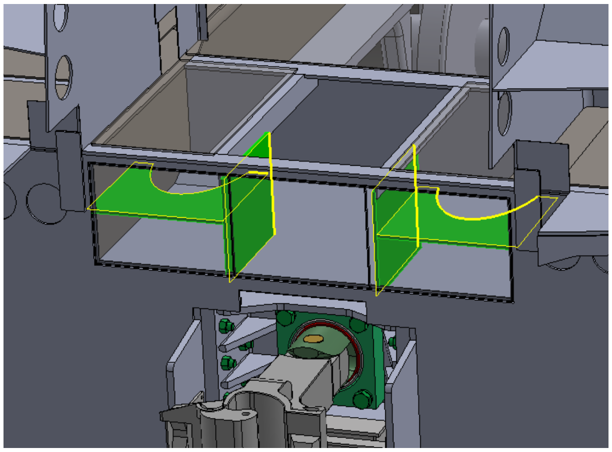


Figure 12. CAD model of an S-580 compliant F40 locomotive that has been modified to include the DAC and PBC elements

New stiffening plates were added behind the end plate by making a rectangular opening in it, as illustrated in Figure 13. The end plate was then closed with appropriately sequenced welded-up plates to permit good welding.



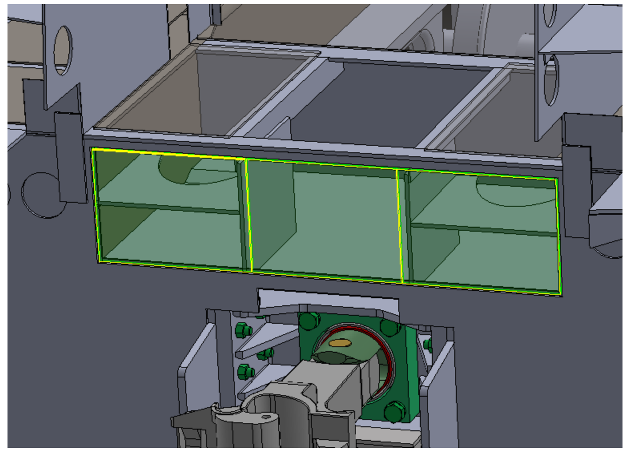


Figure 13. New stiffening plates added behind the end plate

As shown in Figure 14 and Figure 15, a plate was added in the same plane as the end plate to form a front flange for the collision post. Holes were cut into the collision post forward of the flange plate to reduce its crush strength. The lower, central region of the short hood nose was cut out to allow the DAC tubes to crush. A 16 gauge (0.065 inch) sheet was used to close off the DAC structure from the short hood. This sheet was only tack-welded to the end frame.

As illustrated in Figure 15, the collision post front flange extended downward below the floor to lap over the end plate. Calculations indicated that the shortened collision post web and existing welds met the S-580 shear requirement of 550 kips ultimate strength. The length of extension below the floor was determined based on the force developed in the flange due to S-580 loading, assuming 5/16 inch fillet welds.

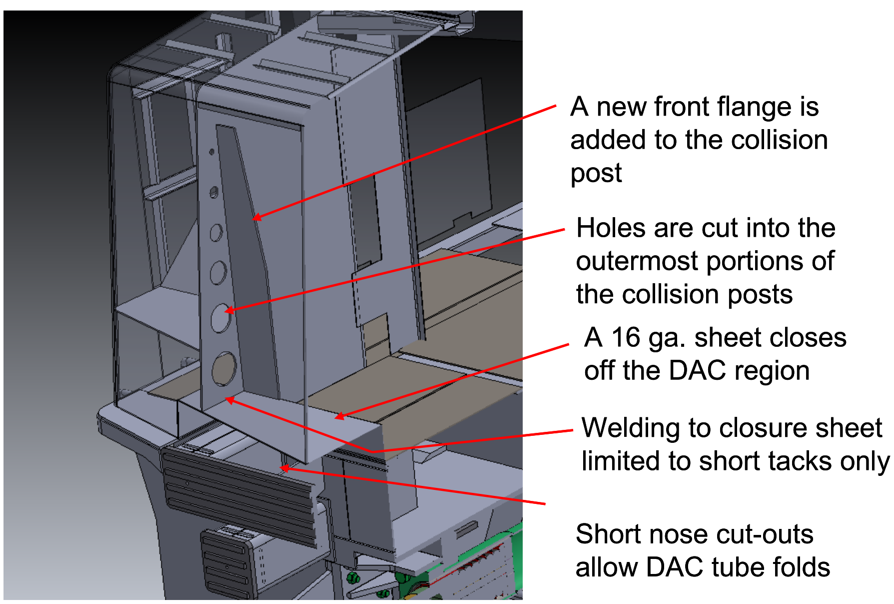


Figure 14. Modifications to collision post and short hood nose

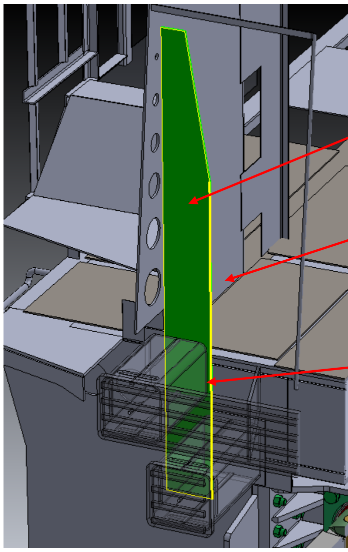


Figure 15. Added collision post flange

The DAC structure is highlighted in Figure 16. Shim plates were added on either side of the collision post flange where it extended below the floor to provide structure to which to weld the crush tubes. These plates had the same thickness as the collision post flange plates. The spacing of the upper tubes (57 inches center-to-center) was not changed from the MP40 retrofit design. The F40 collision post webs (61.5 inches center-to-center) were in fact more in line with the upper crush tubes than they were for the MP40 design (63.75 inches center-to-center). The lower crush tubes were spaced 38.5 inches apart center-to-center, as they were for the MP40 design. Both sets of tubes were slightly (< 0.25 inch) higher than they were in the MP40 design. During preliminary FE analyses, researchers found that the crush behavior of the lower tubes during collision with a cab car would likely be improved if the lower tubes were moved downward. Unfortunately, such a shift might result in interference with the push-back motion of the coupler head in the case of a collision with a cab car that was offset upwards by 3 inches and laterally by 3 inches.

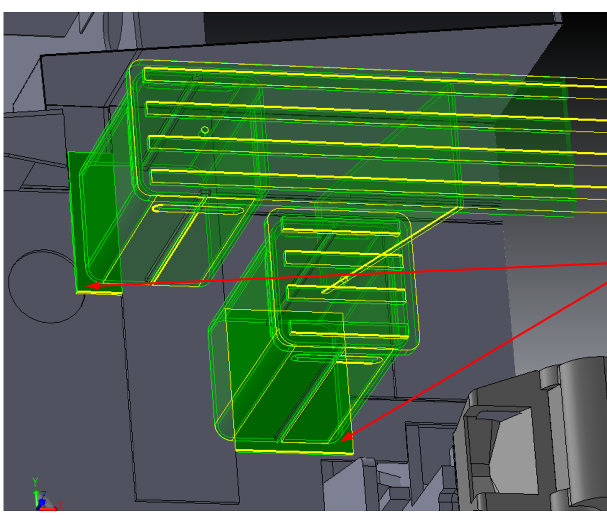


Figure 16. DAC elements and added shim plates

The modified draft pocket design is pictured in Figure 17. The draft pocket design was advanced from that of the MP40 design. A cut-out was designed into the angled back plate so that it did not interfere with the transom bar of the forward truck frame. Figure 19 shows a side view of the PBC assembly where the tight clearances between the back of the draft pocket and the transom bar of the truck frame are evident. The tight clearances are further illustrated in annotated photographs of F40 Locomotive 234 (see Figure 18).

Note that, at the full extent of travel of the PBC and sliding lug, the back of the PBC deformation tube came very close to interfering with the axle cover and traction motor bracket of the forward truck. As is evident in Figure 20, the vertical clearance is less than 1.2 inches.

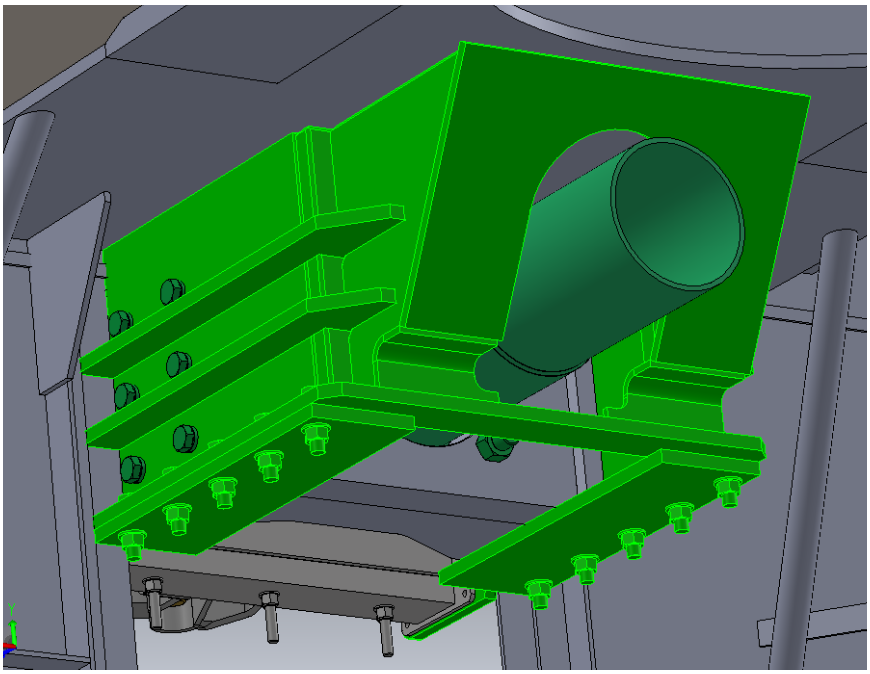


Figure 17. Modified draft pocket design with cut-out at bottom of angled back plate for truck transom clearance

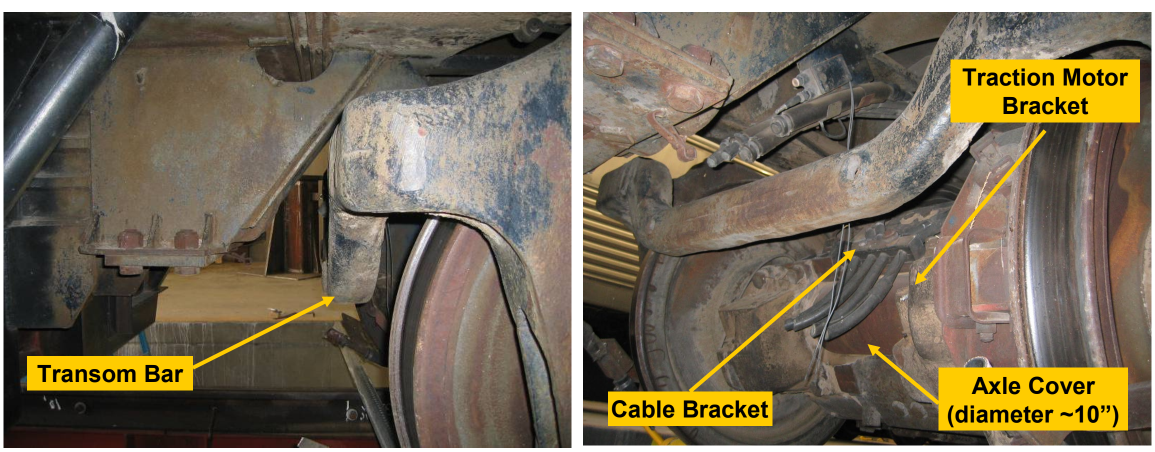


Figure 18. Photographs illustrating the clearance between the existing draft pocket and various components of the forward truck

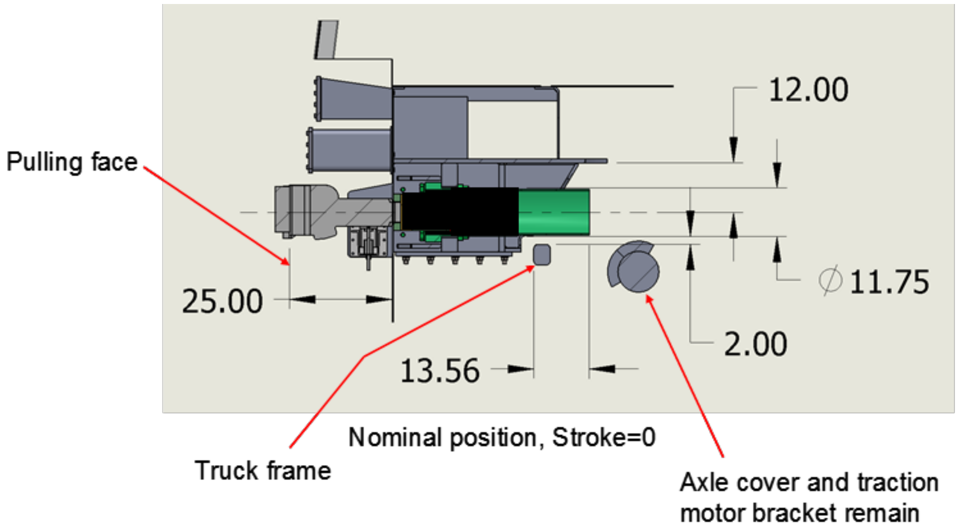
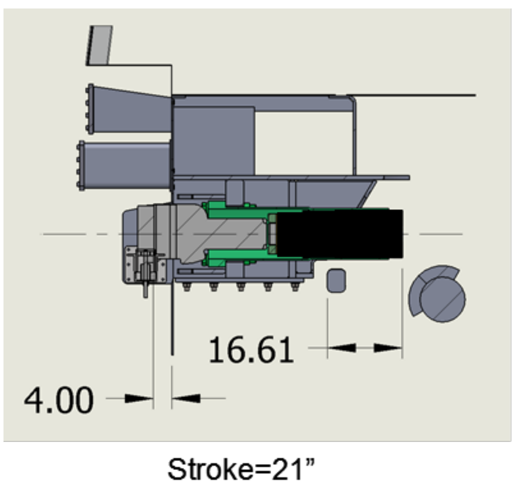


Figure 19. Side view illustration of PBC initial position relative to truck frame and axle cover/traction motor bracket (dimensions in inches)



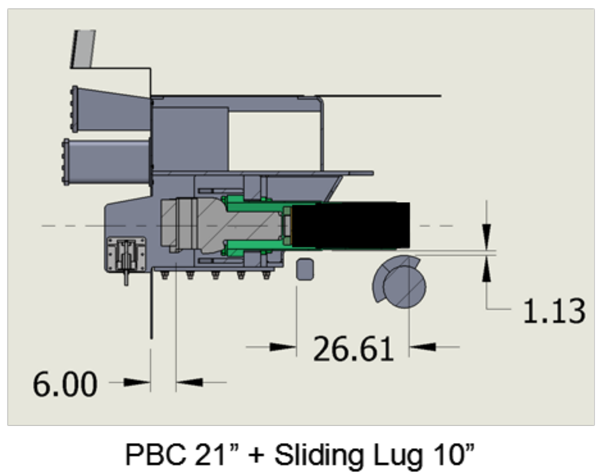


Figure 20. Side view illustration of coupler push-back and resulting clearance with the axle cover/traction motor bracket (dimensions in inches)

The sliding lug (see Figure 21) changed very little from the MP40 design. It was made slightly taller (21.7 inches vs. 19.3 inches) to accommodate differences in the respective underframe geometries, but was otherwise unchanged, with a width of 30 inches and a longitudinal depth of 15.625 inches.

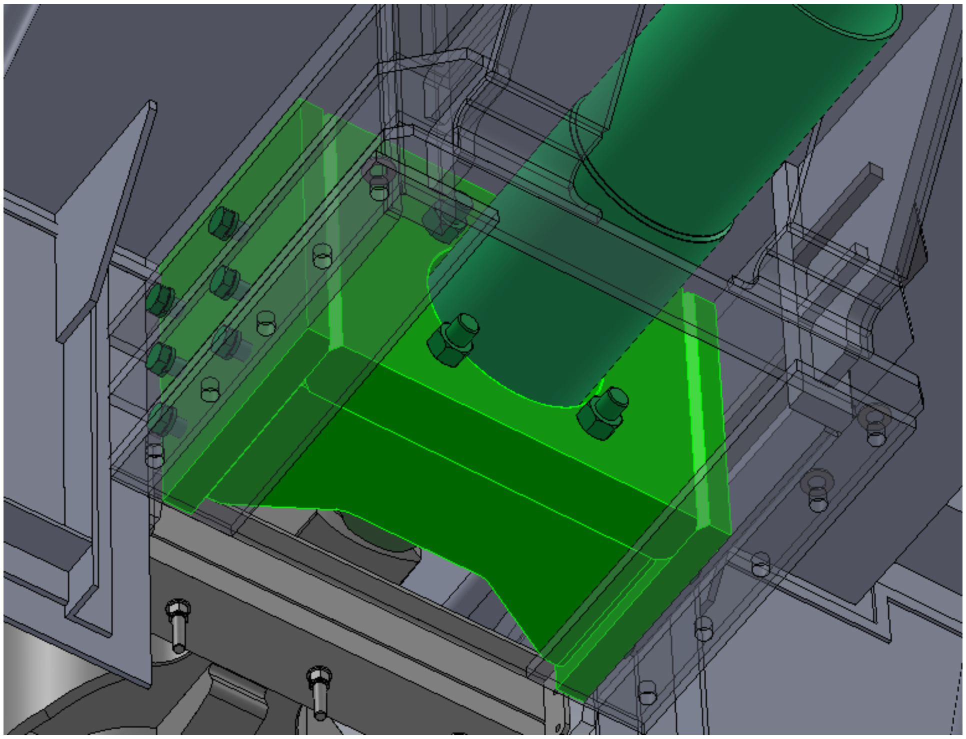


Figure 21. The sliding lug design

One minor modification to the design was made based on the results of preliminary FE analyses for the locomotive-into-wall collision scenario (see Section 3.2), which had not been examined during the original design development. In this scenario, the front portions of the side walls of the draft pocket, where they were forward of the end plate and support the coupler carrier, impacted the wall before the DAC tubes fully crushed. In an actual collision between two such modified-locomotives, these thick plates would impact with one another, resulting in very large forces. Based on these preliminary FE analysis results, these plates have been modified so that they had a small lateral kink (see Figure 22) and were thinner so that if they did interact with one another, the transmitted load would be much smaller. They were also tapered so that the length of the front edge of the plate was 3 inches smaller than the length of the rear edge of the plate.

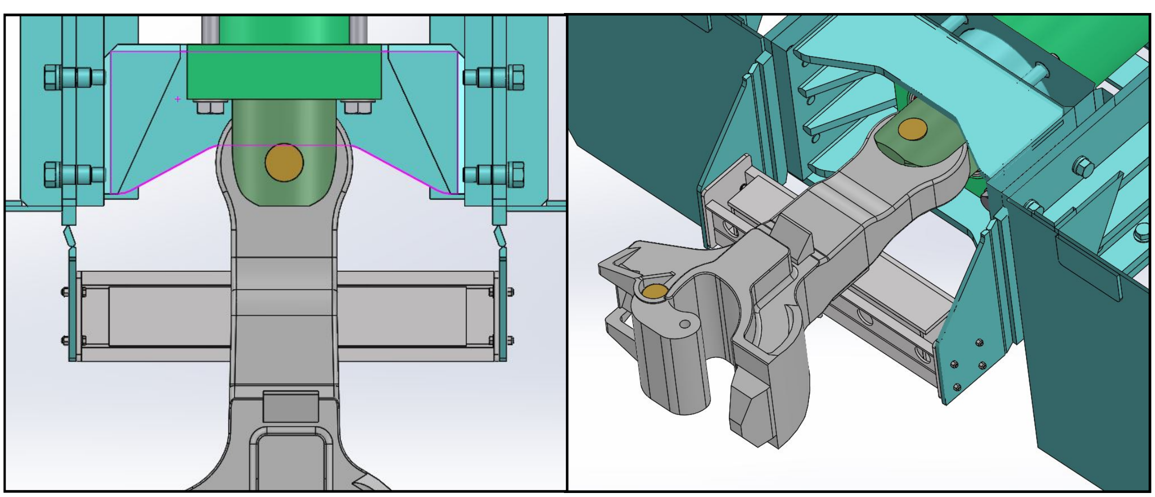


Figure 22. Modified plates that form the sides of the draft pocket, where they extend forward of the end plate

4.2 Finite Element Models

The FE-based evaluation of the F40 retrofit was aimed at evaluating the consequences of four collision scenarios:

- Modified F40 locomotive into a rigid wall
- Modified F40 locomotive into a conventional (i.e., un-modified) F40 locomotive
- Modified F40 locomotive into a conventional cab car
- Modified F40 locomotive into a conventional freight car

As noted earlier in this report, a Bombardier model M1 was selected to represent a conventional cab car, and a Trinity Rail center beam flat car was selected to represent a conventional freight car.

Using the CAD model of the modified and un-modified F40 locomotives described in the previous section, drawings for the F40 locomotive and the M1 cab car, new FE models for these vehicles were constructed. TIAX reviewed existing FE models for the F40 locomotive that had been used in earlier programs. Researchers found that these models, which were several years old, were not suitable for this program. Therefore, new models for both the conventional and modified F40 locomotives were built from "scratch" using Abaqus/CAE [11]. The 3-dimensional CAD models of the end frame that Canarail constructed for these vehicles were used as guides for building shell-based models of the respective vehicles. Structures common to both vehicles were defined separately from structures that were present in only one of the two vehicles.

Similarly, an existing model of a state-of-the-art cab car was available for modification and use in this program; however, researchers determined that the end structure of a conventional M1 cab car differed greatly from that of the state-of-the-art cab car, and they decided to build an M1 model from scratch using Abaqus/CAE.

An existing model of a Trinity Rail center beam flat car was also available for modification and use in the program. This model was built to represent only the forward half of the freight car. To be consistent with the other vehicle models and so single vehicle-to-single vehicle collisions could be properly modeled, researchers extended this model to represent a complete freight car.

As noted, all models were constructed using Abaqus/CAE. The new vehicle models for the modified and conventional locomotives and the M1 cab car were constructed using an approach in which car body assemblies and, in some cases, sub-assemblies were defined as independent entities which could then be integrated to create the entire vehicle assembly. Any changes to individual parts (and each vehicle had several hundred) could be made within the confines of the assembly or sub-assembly so that the vehicle model could be easily re-assembled with the revised parts. This approach was not used for the freight car model, as it was not originally built in this fashion. However, the existing model data for this model could easily be de-constructed into individual assemblies (or sub-assemblies).

4.2.1 Un-modified F40 Locomotive

The FE model for the un-modified F40 locomotive is shown in Figure 23. It was constructed from an Abaqus/CAE model with 186 parts grouped into several assemblies and sub-assemblies. The FE mesh consisted of approximately 60,000 elements. In CAE, the vehicle was broken into two regions, separating the forward few feet of the car body from the remaining 50+ feet. Regions modeled with deformable elements are shown in blue and regions modeled as rigid bodies are shown in grey. The characteristic element size used for most of the vehicle was 4.0 inches; a default size of 2.0 inches was used in the forward few feet of the vehicle to improve solution accuracy. However, the collision posts, forward apron and forward gusset plates were assigned a default size of 1.0 inch.

Material properties consistent with A36 steel were assigned to most of the structures in the locomotive. Properties of the collision post which had been modified to S-580 standards were defined to be consistent with A572-50. The density of the rigid structures (trucks, fuel tank, long hood) were established so that the trucks weighed approximately 32,000 lbm each and the entire vehicle weighed approximately 260,000 lbm.

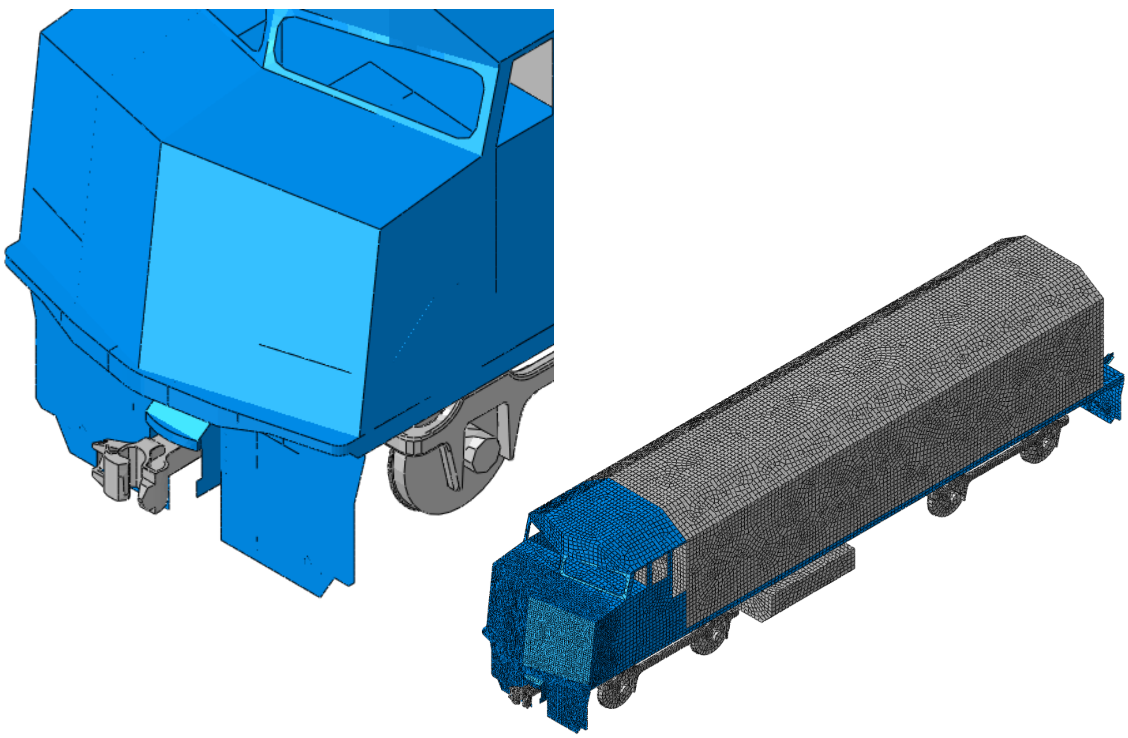


Figure 23. FE model for the un-modified F40 locomotive: right—whole vehicle with elements shown; left—detail of forward end with elements removed

4.2.2 Modified F40 Locomotive

The locomotive modified to include the PBC and DAC components is shown in Figure 24. Regions modeled with deformable elements are shown in blue; regions modeled as rigid bodies are shown in grey. This mesh was created from an Abaqus/CAE model with 221 parts. The mesh was defined in a manner similar to that of the conventional locomotive, with most of the vehicle modeled with a mesh spacing of 4.0 inches, and with the forward end modeled with a mesh spacing of 2.0 inches. For this vehicle, the collision post, the apron, the draft pocket and the sliding lug were assigned a mesh spacing of 1.0 inch.

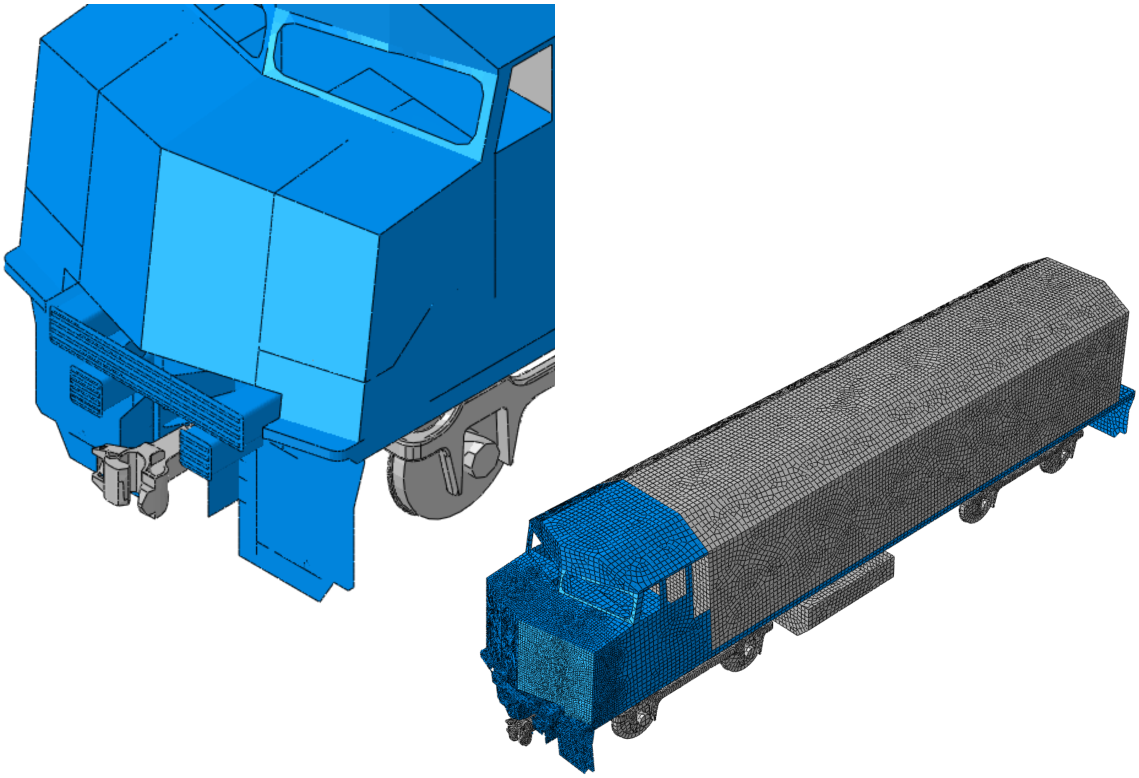


Figure 24. FE model for the modified F40 locomotive: right—whole vehicle with elements shown; left—detail of forward end with elements removed

Elements comprising the DAC was assigned a default size of 0.5 inch, but the crush tubes were assigned a finer mesh spacing of 0.25 inch. Twelve small circular regions in the side walls of the draft pocket, where the shear bolts are attached, were also assigned a mesh spacing of 0.25 inch (see Figure 25). These small circular regions were further defined to be rigid so the load from connector elements representing the shear bolts could be distributed over a region approximating the size of the bolt head.

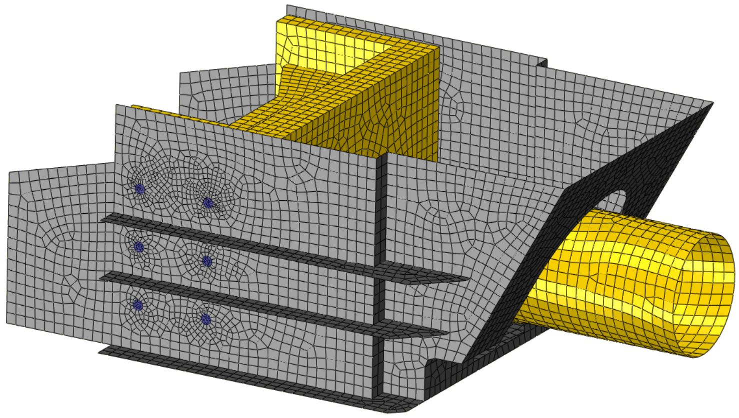


Figure 25. Detailed view of draft pocket from the FE mesh of the modified locomotive

The components added to strengthen the modified locomotive (see Figure 13 through Figure 17) were assigned to have properties consistent with A572-50. The crashworthy components were also assigned properties of A572-50, with the DAC further defined to have properties consistent with a Bao-Wierzbicki failure model [11], as had been done in the prior program.

4.2.3 Cab Car

An FE model for the M1 cab car was constructed in Abaqus/CAE. Regions modeled with deformable elements are shown in blue and regions modeled as rigid bodies are shown in grey. An FE mesh with 184,000 elements was defined based on an Abaqus/CAE model with over 400 parts separated into several assemblies/sub-assemblies. The car was divided into three regions for assigning mesh density. The back 67+ feet were assigned a mesh spacing of 4.0 inches. A region of length 11+ feet forward of the back region was assigned a mesh spacing of 2.0 inches, and a region at the front of the car of length 7+ feet was assigned a mesh spacing of 1.0 inch. The collision posts, collision post lugs, and buffer beam were further assigned a mesh spacing of 0.5 inch.

Most of the cab car components were defined to have properties of RY306 steel (S_Y = 80,000 psi, S_U = 90,000 psi at 18 percent elongation). A true stress-strain hardening curve similar to that which had been fit to the measured A572-50 data in the prior program was fit to these data.

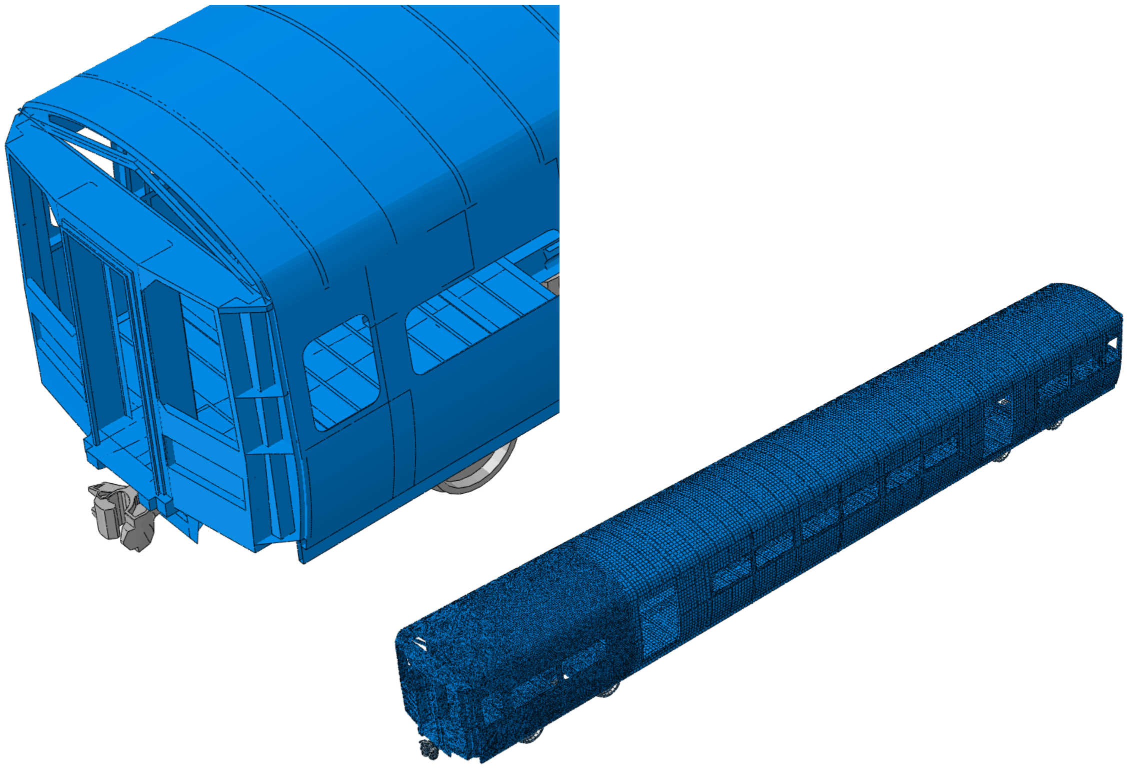


Figure 26. FE model for the M1 cab car: right—whole vehicle with elements shown; left—detail of forward end with elements removed

4.2.4 Freight Car

An FE model for the Trinity Rail center beam flat car (see Figure 27) was modified from an existing half-car model in Abaqus/CAE. Regions modeled with deformable shell elements are shown in blue, solid elements (cargo load only) are shown in green, and regions modeled as rigid bodies are shown in grey. An FE mesh with 192,000 elements was defined based on an Abaqus/CAE model with approximately 50 parts separated into several assemblies. The car was divided into three regions for assigning mesh spacing. The rear 55+ feet were assigned a mesh spacing of 4.0 inches. A region of length 15+ feet forward of the rear region was assigned a mesh spacing of 2.0 inches, and a region at the front of the car of length 5+ feet was assigned a mesh spacing of 1.0 inch. Approximately 85,000 of the 192,000 elements were solid elements that were used to represent a cargo load of about 220,000 lbs. These elements were assigned elastic-plastic properties (E= 50,000 psi, S_Y =1000 psi) that caused the simulated cargo to be relatively compliant, so that most of its strength was due to inertial effects.

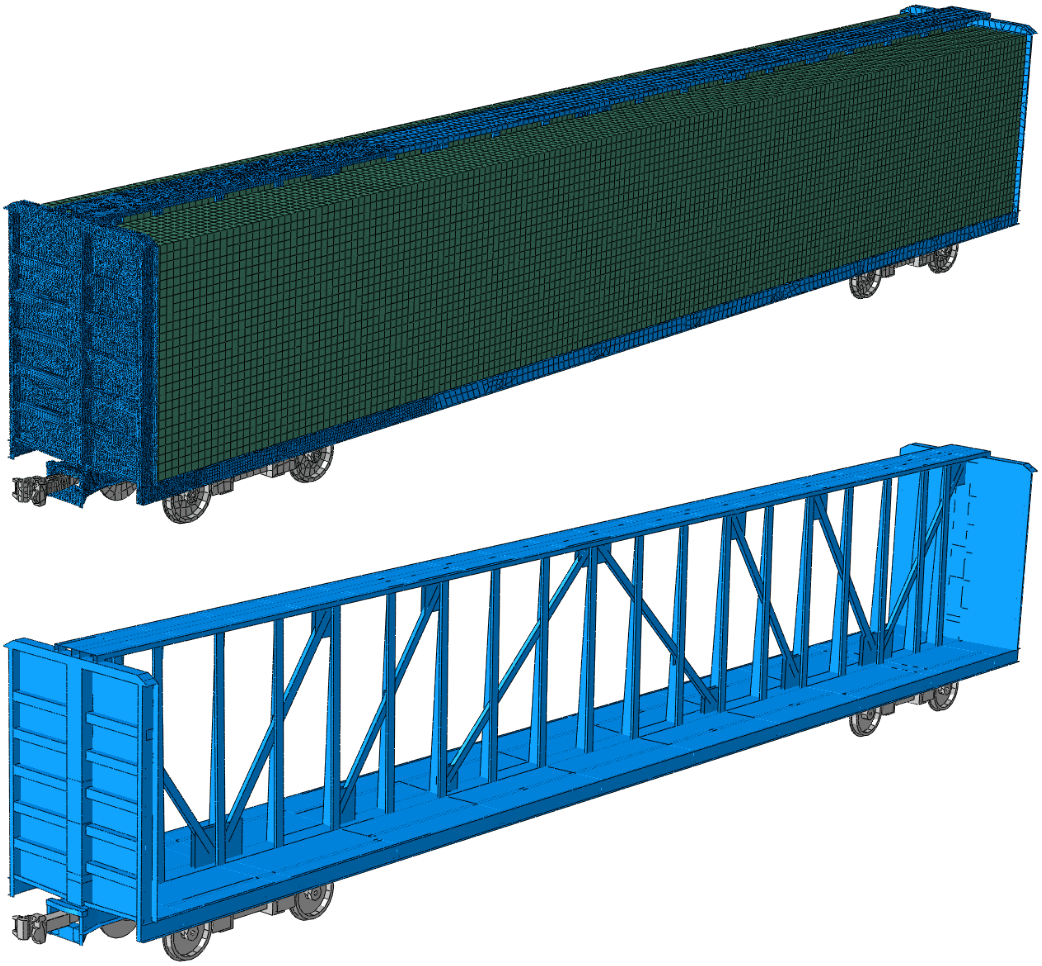


Figure 27. FE model for the Trinity Rail center beam flat car: above—whole vehicle, including cargo load, with elements shown; below—whole vehicle, but without solid elements representing cargo load, and with element outlines removed

5. Evaluation of Retrofit Design

The draft designs outlined in Section 3 were evaluated in simulations of the four collision scenarios described in Section 2 using explicit dynamic finite element analysis (FEA). The Abaqus/Explicit [12] FEA code (version 6.8.4) was used to conduct the analyses.

For all of the simulations, a fixed, rigid surface modeling the ground was defined. Wheel-to-ground surface contact was modeled as frictionless so the wheels could move freely along the rail. Gravity was modeled as on for all simulations. Contact between deformable surfaces was modeled with a friction coefficient of 0.3. The rigid surfaces representing the trucks were constrained with respect to lateral displacement, yaw, and roll, but were left free with respect to longitudinal and vertical displacement and pitch. A body force representing gravity was applied in the downward direction. This force was ramped up over the first 0.01 second of the simulation so as to avoid the sudden acceleration associated with a step in force.

5.1 Modified Locomotive into Wall

In the first collision scenario, the modified locomotive collided with a rigid flat wall at an impact speed of 22 mph. Contact between the modified locomotive and the rigid flat wall was modeled with a friction coefficient of 0.3. Note that the impact speeds for all of the collision scenarios were selected, through some trial-and-error, to be sufficient to deform the two crashworthy components and determine the point at which the deformation of other structures in the end frames of the colliding vehicles began to dominate the response. For this reason, the collision speeds were different for each scenario.

Since this scenario was meant to model an impact with another modified F40 locomotive, the slight asymmetry that was added to the plates that supported the coupler carrier so that they did not impact the corresponding plates on the other locomotive (see Figure 22) was modeled simply by not defining contact between these plates and the wall.

Side views of the undeformed configuration for this model are shown in Figure 28.

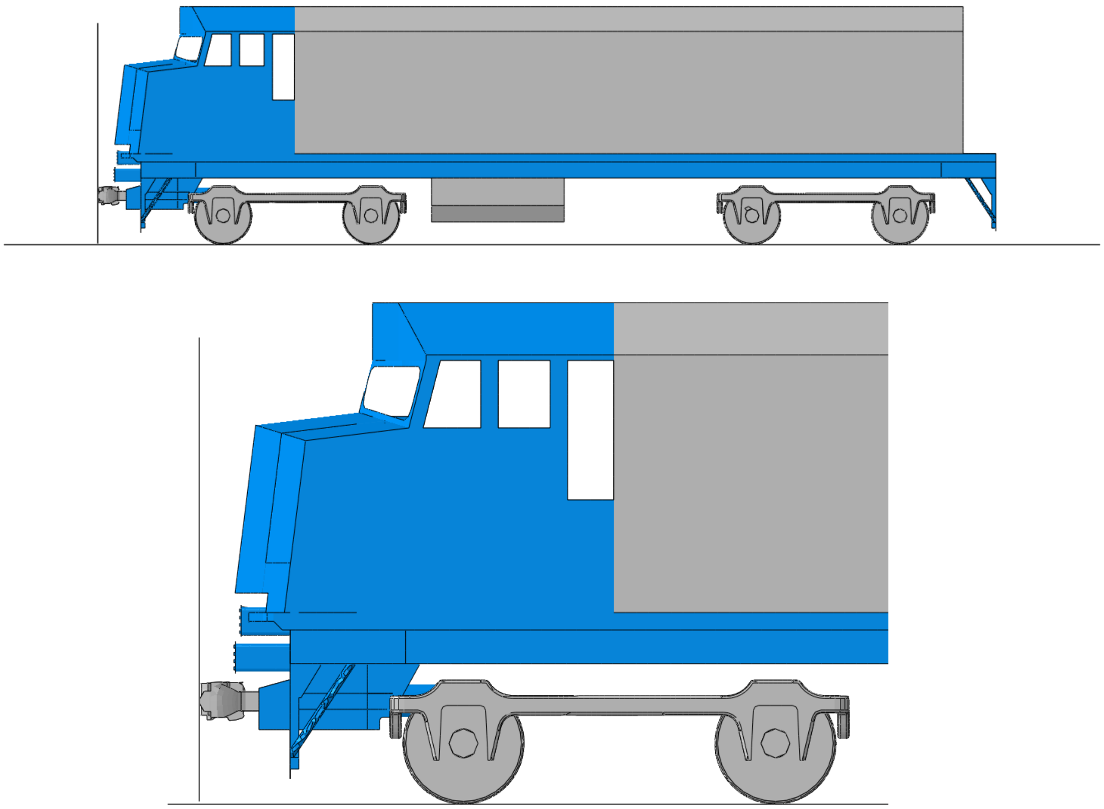


Figure 28. Side views of the modified locomotive-into-rigid wall FE model in the undeformed configuration: top—entire vehicle; bottom—detail near colliding interface

The results of the simulation of a 22 mph collision of the modified locomotive into a fixed rigid wall are summarized below. An annotated force versus displacement curve is shown in Figure 29. In this curve (as in all of the force-displacement curves calculated for the collision scenarios), displacement represents the relative motion of the centers of the respective vehicles toward one another, and force is calculated as *dE/dU* and filtered at CFC 180, where E is total strain energy (Abaqus ALLIE) and U is vehicle displacement, which is measured at a point near the center of gravity (CG) of the vehicle (i.e., away from regions undergoing large deformation).

The force built up to the design target 674,000 lbf push-back load of the deformation tube element after 3 inches displacement, and then leveled off. After 12 inches of crush, the lower DAC tubes impacted the wall and began to crush, and the load rose significantly. After 14 inches of crush, the upper DAC tubes impacted the wall and began to crush, and the load rose further, to over 2 million lbf. The load stayed near this same level until the travel of the deformation tube element was exhausted after 22 inches of crush, and the load through the coupler quickly built up to the point where the shear bolts failed. The load decreased to just over 1 million lbf and then quickly started to rise again as the DAC tubes began to consolidate.

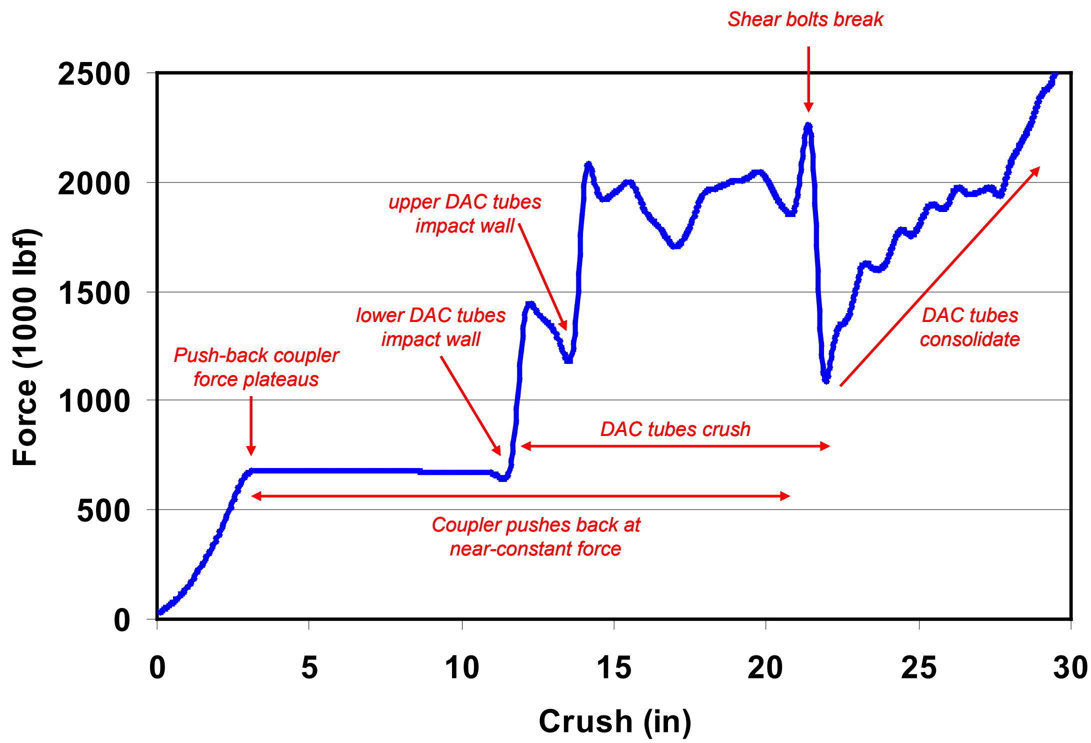


Figure 29. Collision of the modified locomotive into a flat, rigid wall: annotated force versus displacement curve

With regard to the use of *dE/dU* as the measure of collision force, note that force can also be calculated as $F = ma$, where m is the mass of the vehicle (or vehicles) and a is the acceleration of the vehicles toward one another. However, based on the authors' experience, this measure was noisy, due to high-frequency longitudinal oscillations associated with elastic deformation of various components. For the case of the collision of a single vehicle into a wall, the force can be calculated *directly* as the sum of the reaction forces against the wall.

For comparison, all three of these measures of force versus displacement are plotted in Figure 30. As is apparent, the $F=ma$ measure is indeed noisy, while the $F=dE/dU$ measure is more consistent with the *direct* measure of force against the wall (which also exhibits oscillations that are likely due to high-frequency elastic deformation). Note also that it can be shown that, if one assumes that all of the kinetic energy of the system is converted to strain energy (and not dissipated by friction or converted to artificial energy), then it can be shown that $F=dE/dU$ is equivalent to calculating the force as $F = ma'$, where in this case, a' is equal to dv'/dt, where v' is calculated from the definition of kinetic energy as $v'=(2*E_k/m)^{1/2}$, treating the system as equivalent to that of a lumped mass m positioned at the CG of the system.

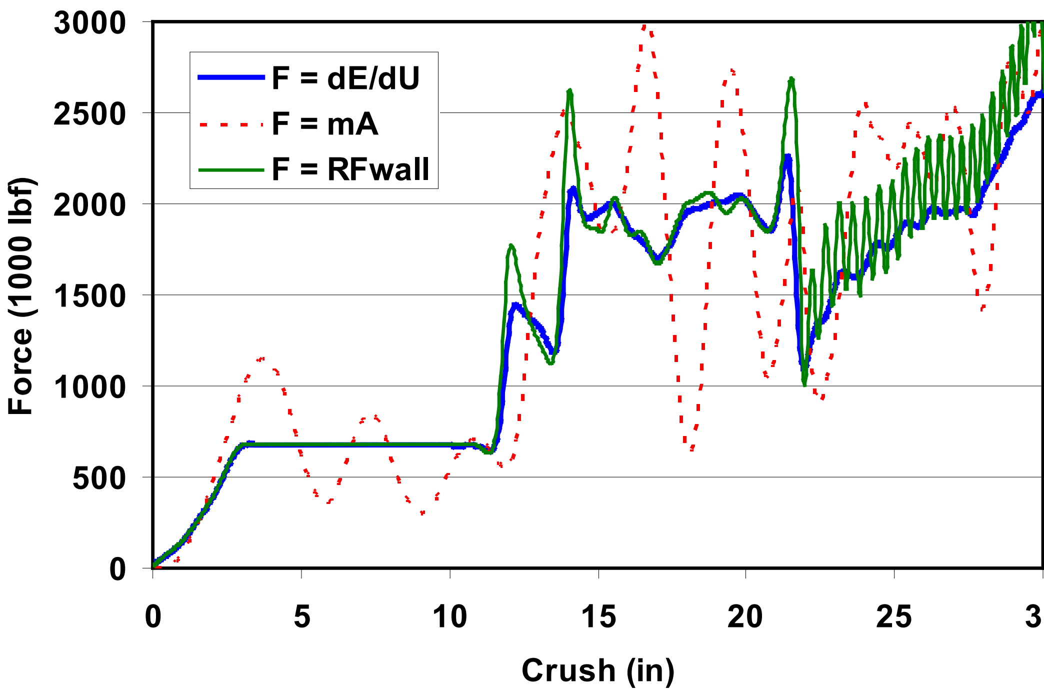


Figure 30. Comparison of three measures of force vs. displacement for the modified locomotive colliding into a flat, rigid wall

Figure 31 and Figure 32 illustrate the deformation that arose as the vehicles crushed. Consistent with the force-displacement results, after 28 inches of crush, the DAC tubes started to consolidate, and the load began to build significantly. There was also a significant deformation in the front wall of the short hood.

The deformation tube of the PBC was completely pushed back, to the point where its back end was very close to the traction motor bracket of the forward truck. This was partly due to the fact that the front wheels of the forward truck had risen by about 2.3 inches. Note that most of the vertical displacement of the front truck wheels occurred toward the end of the collision. After 22 inches of crush, the vertical displacement was less than 0.9 inches.

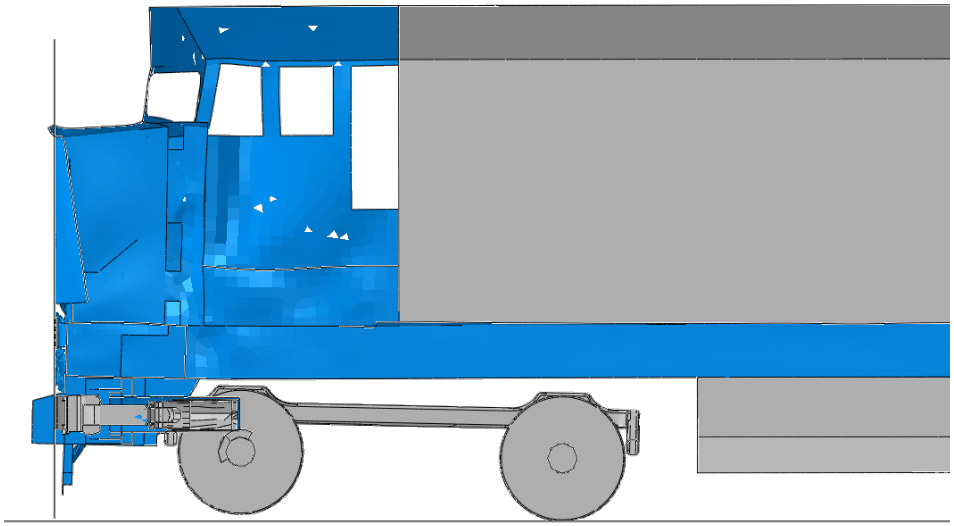


Figure 31. Side view of modified locomotive end frame after approximately 28 inches of crush

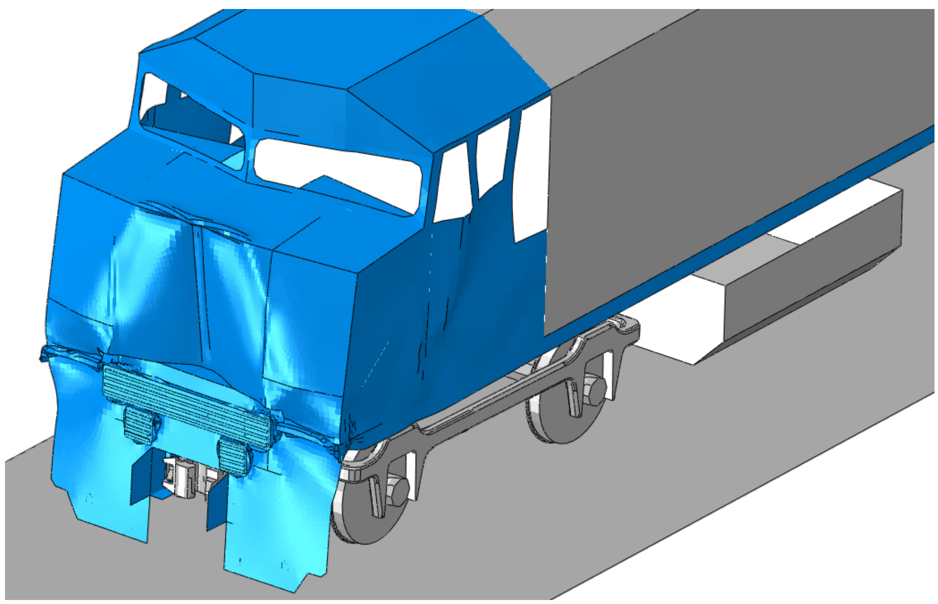


Figure 32. Isometric view of modified locomotive end frame after approximately 28 inches of crush

Figure 33 shows the build-up of energy in the DAC and in the other components in the front end of the modified locomotive that crushed, including the short hood, the anti-climber skirt, and the collision posts. The plateau in the deformation energy versus displacement plots for the upper and lower DAC tubes suggested that they had consolidated to the point where they would not crush much further, but instead would transmit load to the underframe where they were supported. This plateau was also consistent with the sharp rise in load that began at this extent of crush. The energy that had been absorbed by the DAC after 28 inches of crush was approximately 1,160 ft-kips, well above the 600 ft-kips requirement for the system. This was not surprising, given that the tubes crushed in such an efficient manner when impacting the flat wall. The energy absorption in the other components of the front end was about 570 ft-kips. Finally, the PBC, which has exhausted its stroke, had absorbed approximately 1,140 ft-kips, also well above the 600 ft-kips requirement. Calculated energy absorption levels and wheel lift are summarized in Table 1.

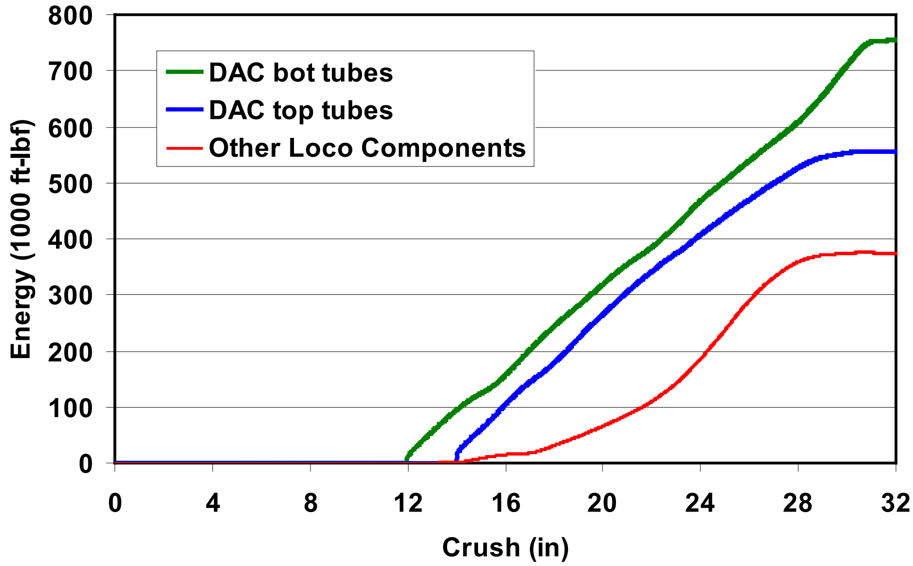


Figure 33. Build-up of deformation energy in the DAC and the other parts of the modified locomotive front end

Table 1. Modified locomotive into a rigid wall: comparison of energy absorption levels (in ft-kips) and peak wheel lift at a crush level of 28 inches

Push-back Coupler	1,100
Deformable Anti-climber	1160
Other Modified Locomotive Structures	570
Total	2,830
Wheel Lift (Modified)	2.3"

5.2 Modified Locomotive into Conventional Locomotive

In the second collision scenario, the modified locomotive collided with a conventional locomotive at an impact speed of 30 mph. Side views of the undeformed configuration, baseline case, are shown in Figure 34. As is evident from this figure, the upper DAC tubes were aligned with the stiff gusset plates of the conventional locomotive anti-climber. The lower DAC plates did not begin to crush until they struck the end plate of the conventional locomotive.

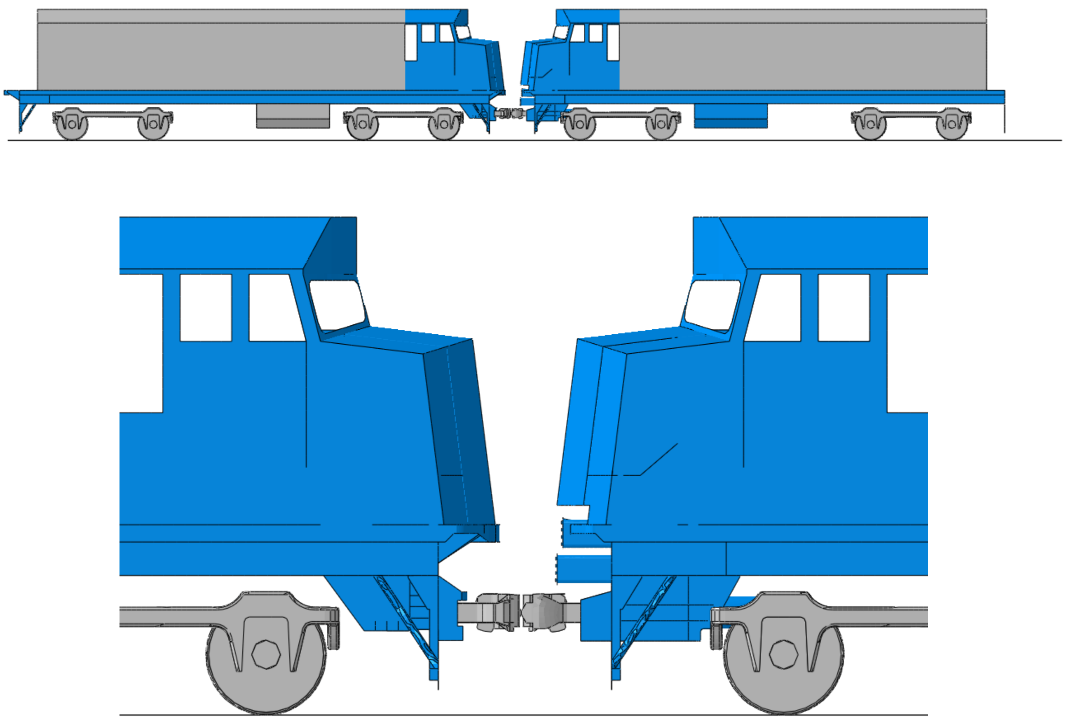


Figure 34. Side views of the modified locomotive-into-conventional locomotive FE, underformed: above—entire two-vehicle model; below—detail of colliding interface

An annotated force-displacement curve for the baseline case is shown in Figure 35. The force built up to the 674,000 lbf push-back load of the deformation tube element, and then leveled off.

After approximately 20 inches of crush, the upper DAC tubes impacted the anti-climber of the conventional locomotive and the load began to build. After 22 inches of crush, the shear bolts broke, and the load dropped to less than 500,000 lbf. Over the next 12 or so inches of crush, the load was relatively constant as the upper DAC tubes crushed. After about 41 inches of crush, the lower DAC tubes impacted the conventional locomotive end plate, and the load began to rise. Shortly after this, the upper DAC tubes began to consolidate, and the load rose further. From about 43 to 50 inches of crush, the lower DAC tubes continued to crush, but the end structures of the two locomotives, particularly that of the conventional locomotive, also began to crush, and the load rose to about 2 million lbf.

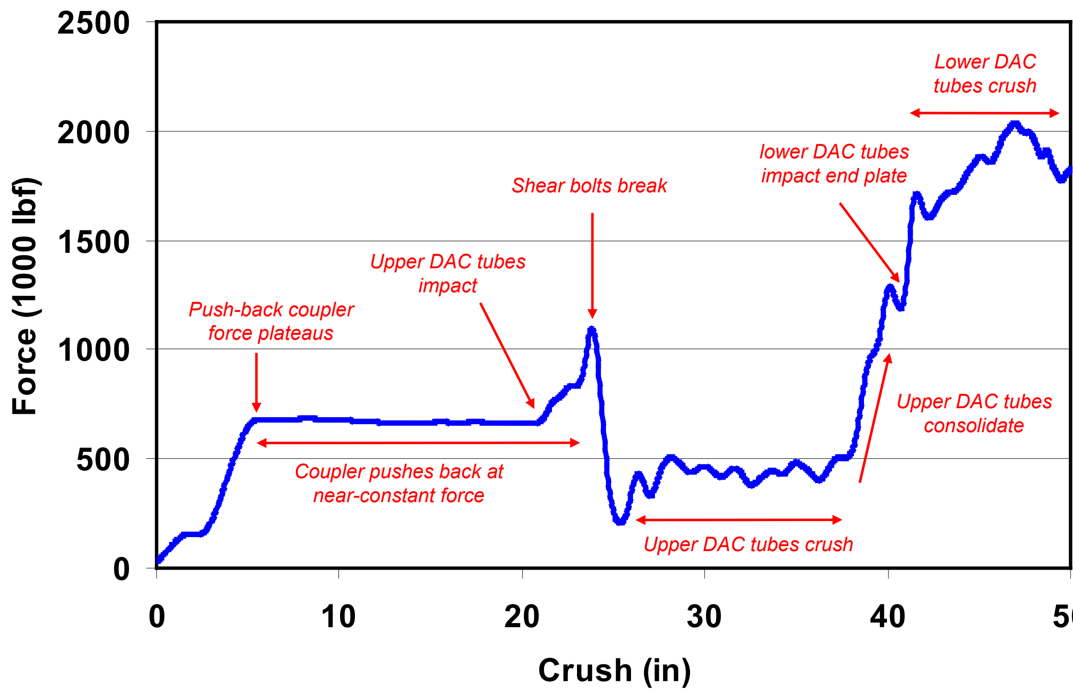


Figure 35. Annotated force vs. displacement curve for collision of the modified locomotive into a conventional locomotive (baseline case)

Side views of the deformed configuration, with the view cut so that the mid-planes of the vehicles are visible, are shown in Figure 36 and Figure 37. Figure 36 shows deformation after 39 inches of crush, at which point the lower DAC tubes had not begun to crush and most of the deformation was in the upper DAC tubes and in the front plate of the short hood. Figure 37 shows deformation after 45 inches, where the lower crush tubes had impacted the end plate of the conventional locomotive and the load had risen significantly. Much more deformation of the end frame was visible at this level of deformation, but the operator's cabs appeared to be more or less intact.

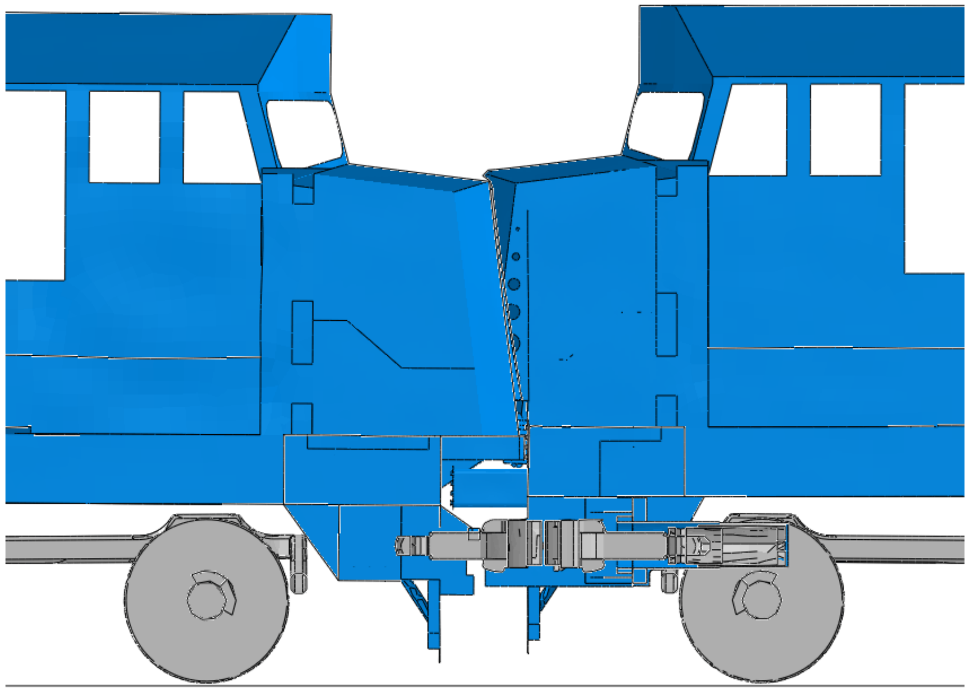


Figure 36. Modified locomotive-into-conventional locomotive (baseline case): side view after approximately 39 inches of crush

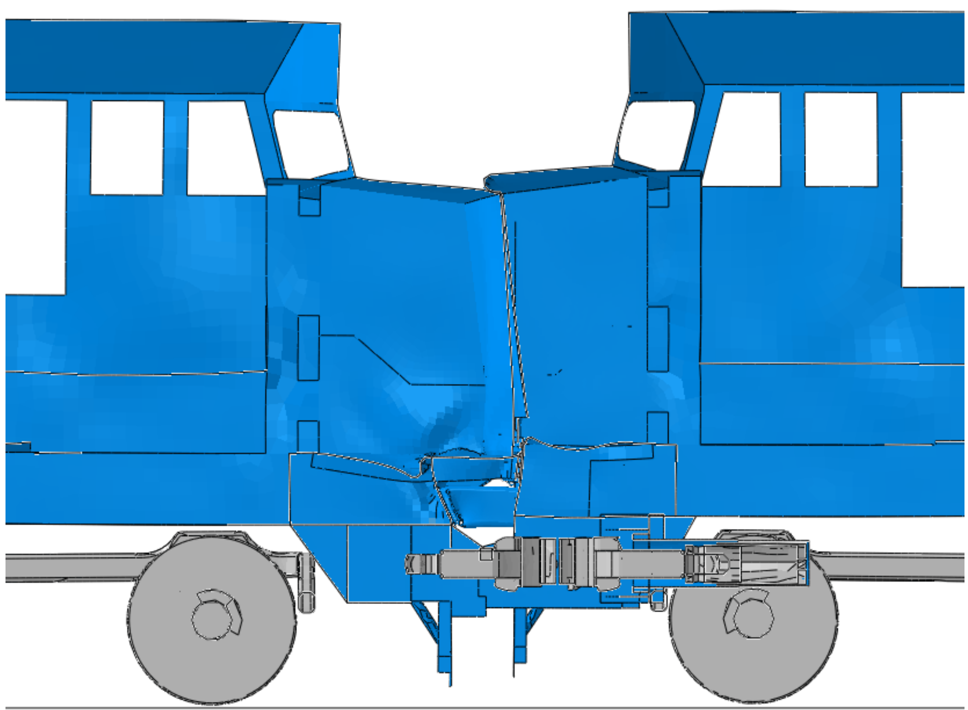


Figure 37. Modified locomotive-into-conventional locomotive (baseline case): side view after approximately 45 inches of crush

In addition to the baseline case in which the two vehicles were aligned, collisions were simulated in which the vehicles were offset by 3 inches both laterally and vertically, with the conventional locomotive raised by 3 inches in one case and lowered by 3 inches in another case (and offset to the right, as viewed from the engineer's position in the cab in both cases). These analyses were conducted for the same collision speed that was used in the baseline analysis. A comparison of the force-displacement curves for the three scenarios is shown in Figure 38. The results for the three cases appeared to be very similar until the crush level reached 38 inches or so, at which point the build-up of load for the offset cases appeared to diverge from that of the baseline case. This was likely due to the different interactions that arose with the DAC and the apron/gusset plates of the conventional locomotive.

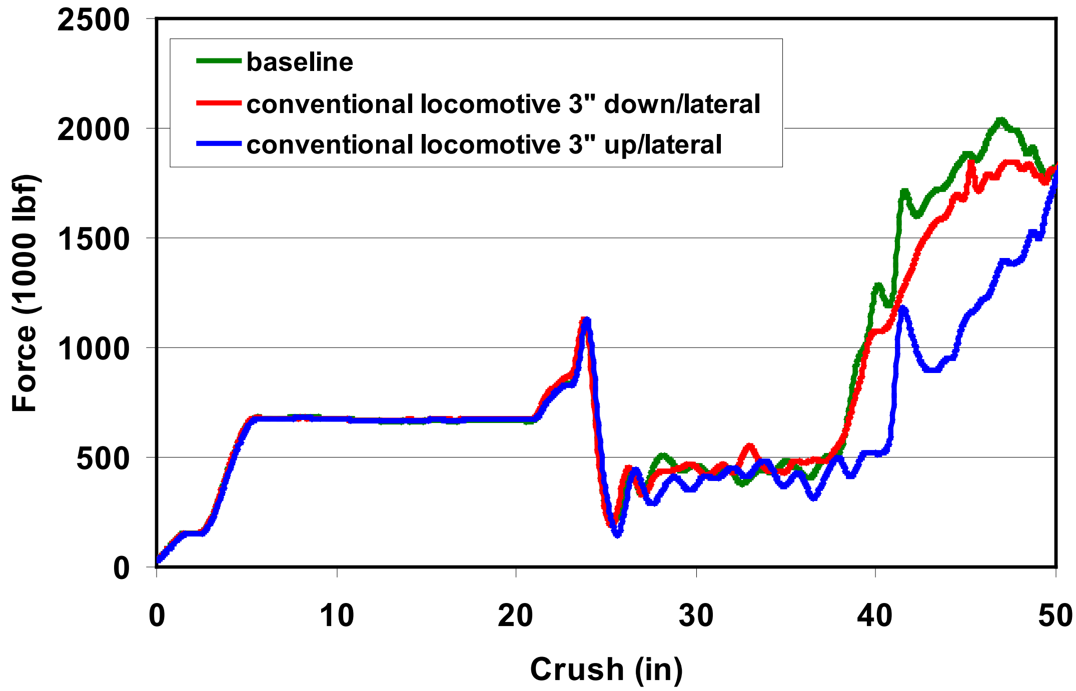


Figure 38. Collision of the conventional and modified locomotives: comparison of force-displacement curves for in-line and offset cases

Figure 39 compares predicted deformation for the three cases at a crush level of 45 inches. The calculated peak wheel lift in the respective forward trucks is also listed in this table. The key difference in behavior that was noticeable in these plots was that, for the case in which the conventional locomotive had been lowered vertically with respect to the modified locomotive, the upper DAC tubes deformed downward appreciably. This likely contributed to the force differences evident in Figure 38 in the 36 inches to 50 inches crush range.

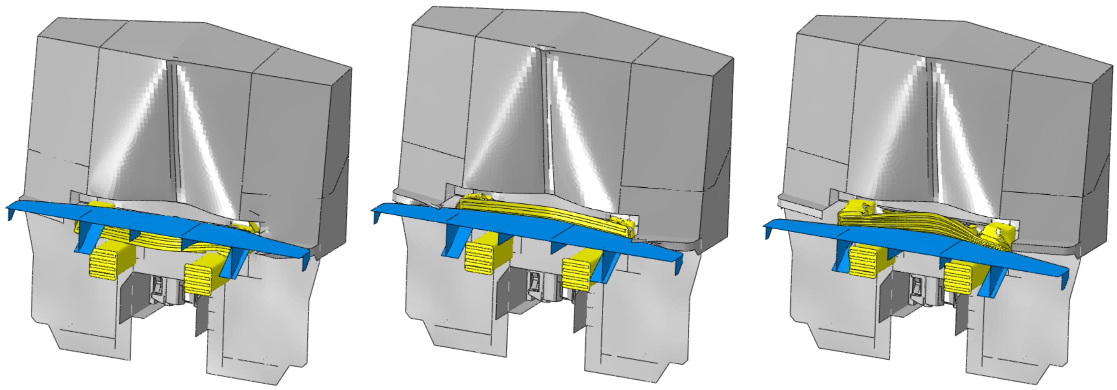


Figure 39. Modified locomotive endframe and conventional locomotive anti-climber: left—conventional locomotive raised by 3 inches and offset laterally by 3 inches; center—vehicles aligned; right—conventional locomotive raised by 3 inches and offset laterally by 3 inches

The energy absorbed by the various components are compared for these three cases in Table 2. These values were calculated at a crush level of 45 inches, at which point the rate of energy absorption in the DAC system had slowed considerably. (Note that, with additional crush, the DAC system, particularly the lower tubes, continued to deform. For example, at a crush level of 49 inches, the energy absorption in the DAC system was over 820 ft-kips. The deformation in the respective end frames was much more significant at this extent of crush.)

Table 2. Collision of the conventional and modified locomotives: comparison of energy absorption levels (in ft-kips) and peak wheel lift at a crush level of 45 inches

	Baseline (In-Line)	Conv. Loco. Shifted 3" Up/Right	Conv. Loco. Shifted 3" Down/Right
Push-back Coupler	1,100	1,100	1,100
Deformable Anti-climber	730	640	660
Other Modified Locomotive Structures	200	100	90
Conventional Locomotive Structures	400	170	510
Total	2,430	2,010	2,360
Wheel Lift (Modified)	1.1"	1.0"	1.1"
Wheel Lift (Conventional)	0.7"	0.8"	0.6"

5.3 Modified Locomotive into Cab Car

In the third collision scenario, the modified F40 locomotive collided with a Bombardier M1 cab car at an impact speed of 40 mph.

Side views of the undeformed configuration are shown in Figure 40. Note that the floor level of the M1 cab car was 49 inches above the top of the rail. This was more than 2 inches lower than the floor level of the state-of-the-art cab endframe previously modeled. As is evident from this figure, the lower DAC tubes (centered at 49.625 inches above the rail) were more-or-less aligned with the top surface of the cab car buffer sill, which was also at 49 inches above rail. The upper DAC plates did not begin to crush until the plate that connected them struck the cab car collision posts, which were set back by about 4 inches from the front of the buffer sill.

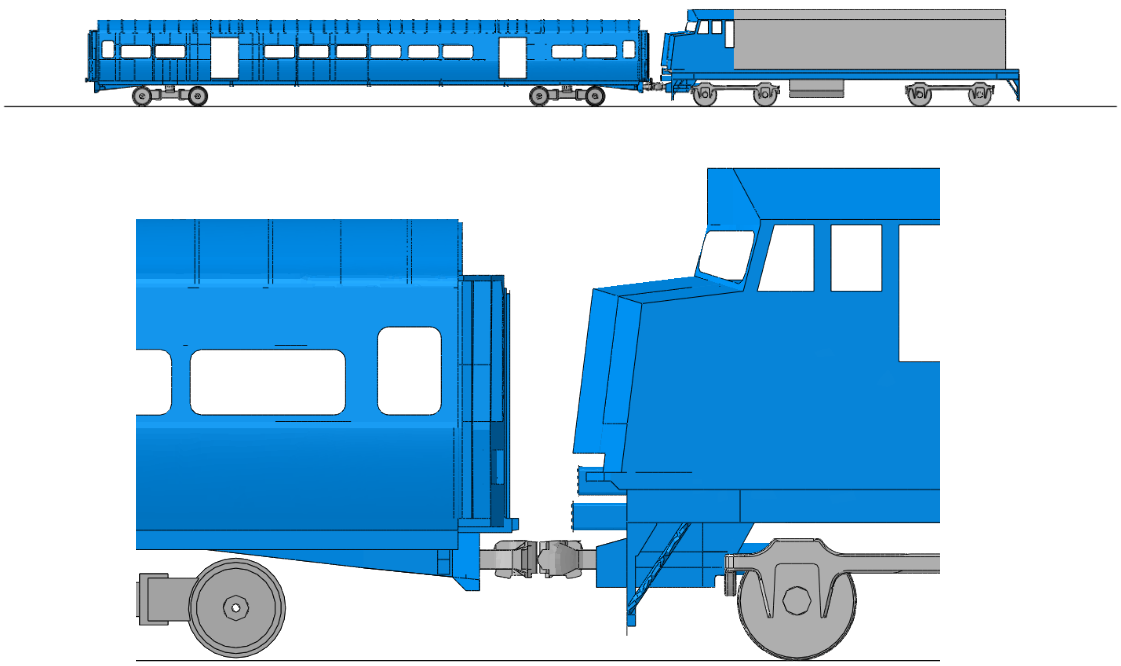


Figure 40. Side views of the modified locomotive-into-cab car FE model in the undeformed configuration (baseline case: vehicles aligned): above—entire two-vehicle model; below—detail of colliding interface

An annotated force-crush curve for the baseline case is shown in Figure 41. The first 18 inches of crush were governed by the push-back of the coupler. At about 18 inches of crush, the lower DAC tubes impacted the anti-climber lugs of the cab car and began to crush. At about 23 inches of crush, the shear bolts broke, and the load dropped. Shortly thereafter, the stiff plate that connected the upper DAC tubes impacted the collision posts, and the upper tubes began to crush. Over the next 12 to 14 inches of vehicle crush, both sets of tubes crushed, and the load remained relatively steady at about 600,000 to 800,000 lbf. After about 42 inches of crush, the M1 draft sill began to buckle, and the load dropped a little. From this point to the end of the analysis (57 inches crush), the load stayed between about 500,000 and 700,000 lbf, but most of the deformation occurred in the M1 cab car.

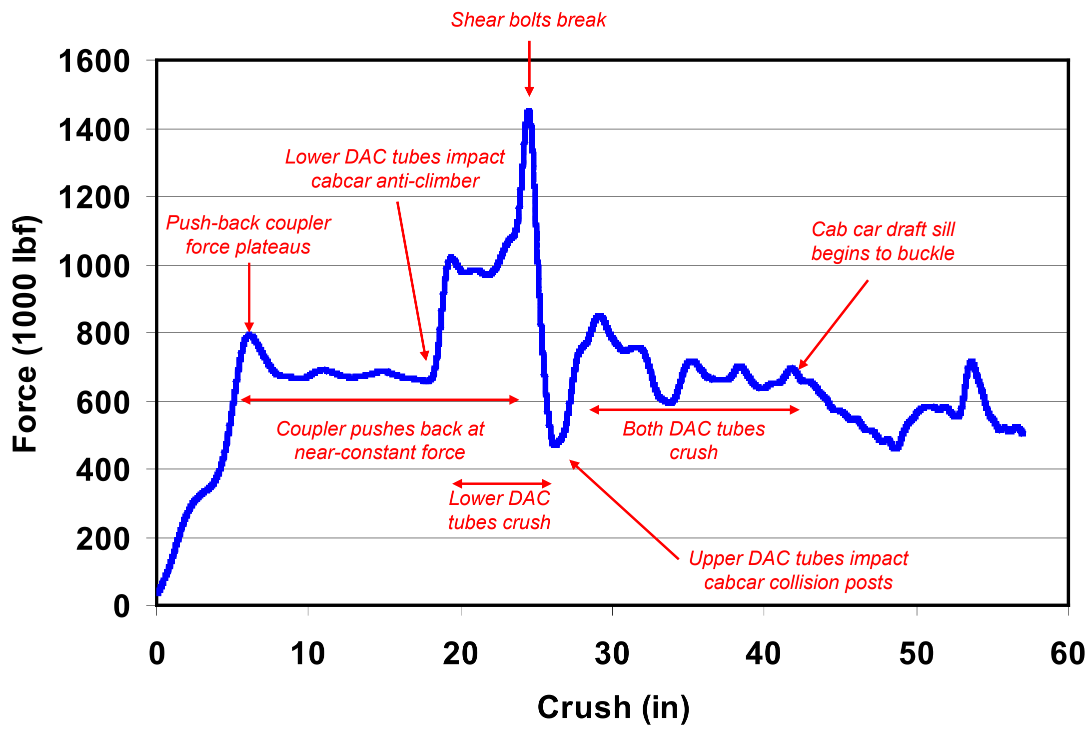


Figure 41. Annotated force versus displacement curve for collision of the modified locomotive into a cab car (baseline case: vehicles aligned)

A side view of the colliding interface at 43 inches of crush is shown in Figure 42. The vehicle ends were completely engaged at this point. The lower crush tubes were extensively crushed, but the top crush tubes were only partially crushed, as the draft sill buckled before they crushed completely. The thick cab car collision post lug did not deform, but rather rotated back as the draft sill buckled.

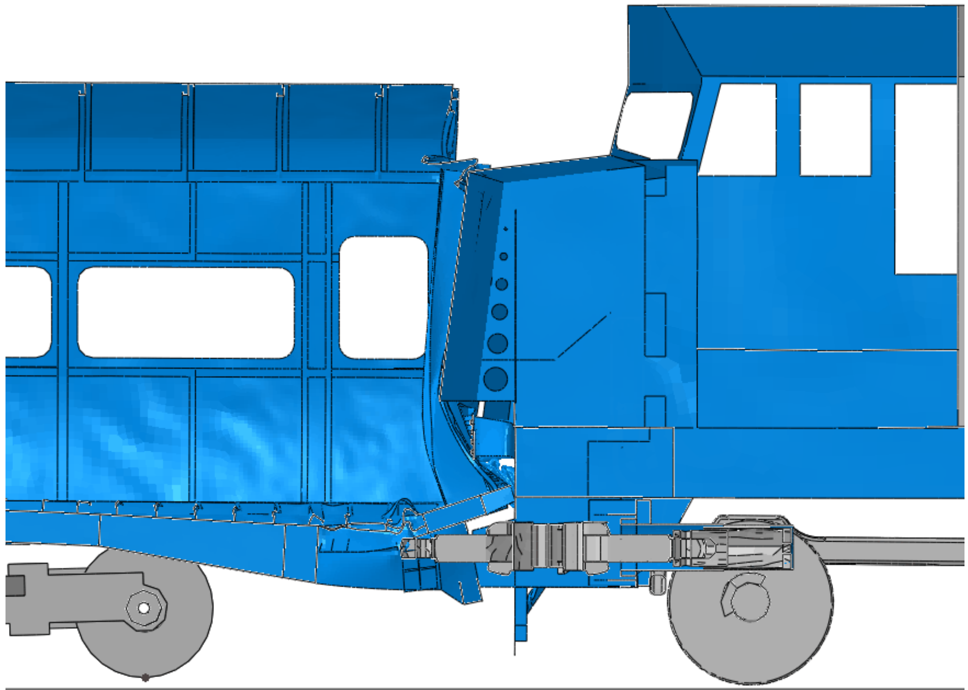


Figure 42. Collision of the modified locomotive into a cab car (baseline case: vehicles aligned): side view of colliding interface after approximately 43 inches of crush

In addition to the baseline case in which the two vehicles were aligned, collisions were simulated in which the vehicles were offset by 3 inches both laterally and vertically, with the cab car raised by 3 inches in one case and lowered by 3 inches in another case (and offset to the right as viewed from the engineer's position in the cab in both cases). These analyses were conducted for the same collision speed that was used in the baseline analysis. A comparison of the force-displacement results for the baseline and offset cases is shown in Figure 43. Two features are noticeable when inspecting these curves:

- The build-up of load following impact of the lower DAC tubes with the cab car after 18 inches of crush was different for the three cases, reflecting the different impact locations for the lower DAC tubes.
- For the case in which the cab car was lowered by 3 inches, the load began to drop right after the upper DAC tubes impacted the cab car collision posts (30 inches of crush). This was because the draft sill of the M1 cab car began to buckle much sooner than in the other cases due to the higher moment.

Table 3 summarizes the extent of energy absorption for the baseline and offset cases for this collision scenario. The calculated peak wheel lift in the respective forward trucks is also listed in this table. The results indicated that, for the baseline case and the case in which the cab car was raised by 3 inches with respect to the modified locomotive, the extent of energy absorption in the DAC system was well over the target of 600 ft-kips. There was also significant energy absorption in the end frame of the cab car. For the case in which the cab car was lowered by 3 inches with respect to the modified locomotive, the extent of energy absorption in the DAC system was below the target of 600 ft-kips because the draft sill buckled before the DAC tubes could crush sufficiently. Note, however, that the energy absorption in the cab car end frame was even higher for this case, and the total for the two vehicle ends, not including the PBC, was almost 1,000 ft-kips.

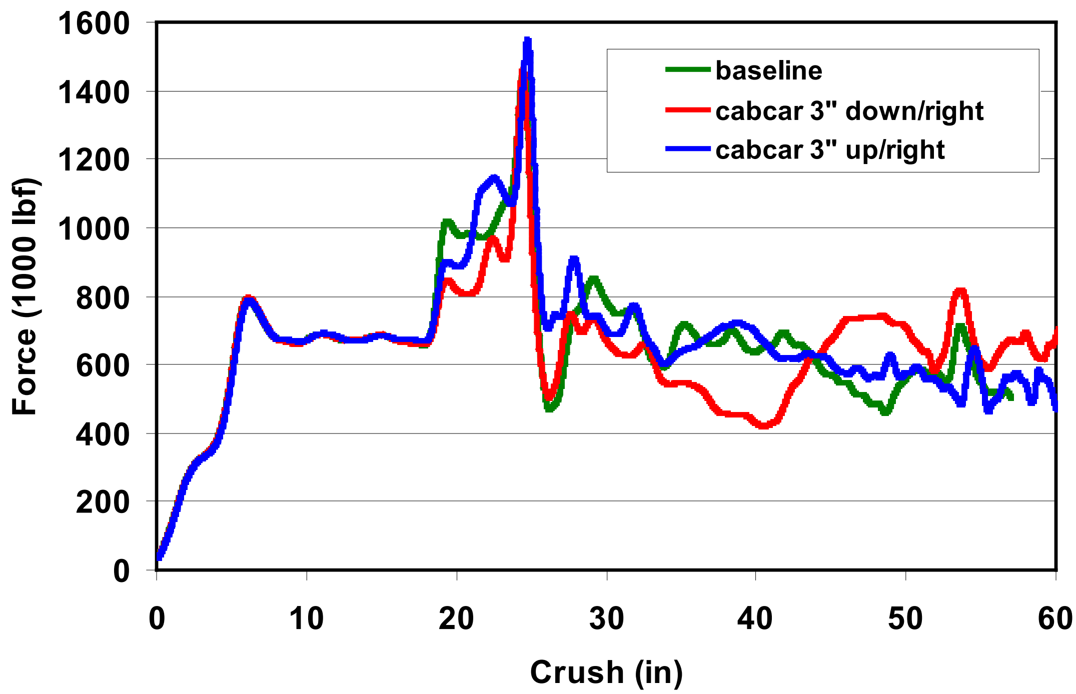


Figure 43. Collision of the modified locomotive with a cab car: comparison of force-displacement curves for in-line and offset cases

Table 3. Collision of the modified locomotive with a cab car: comparison of energy absorption levels (in ft-kips) and peak wheel lift at a crush level of 43 inches

	Baseline (In-Line)	Cab Car Shifted 3" Up/Right	Cab Car Shifted 3" Down/Right
Push-back Coupler	1,100	1,100	1,100
Deformable Anti-climber	740	720	430
Other Modified Locomotive Structures	0	0	0
Cab Car Structures	440	470	520
Total	2,280	2,290	2,050
Wheel Lift (Locomotive)	1.0"	1.0"	0.9"
Wheel Lift (Cab Car)	2.0"	2.3"	1.3"

5.4 Modified Locomotive into Freight Car

In the final collision scenario, the modified locomotive collided with a Trinity Rail center beam flat car at an impact speed of 30 mph.

Side views of the undeformed configuration are shown in Figure 44.

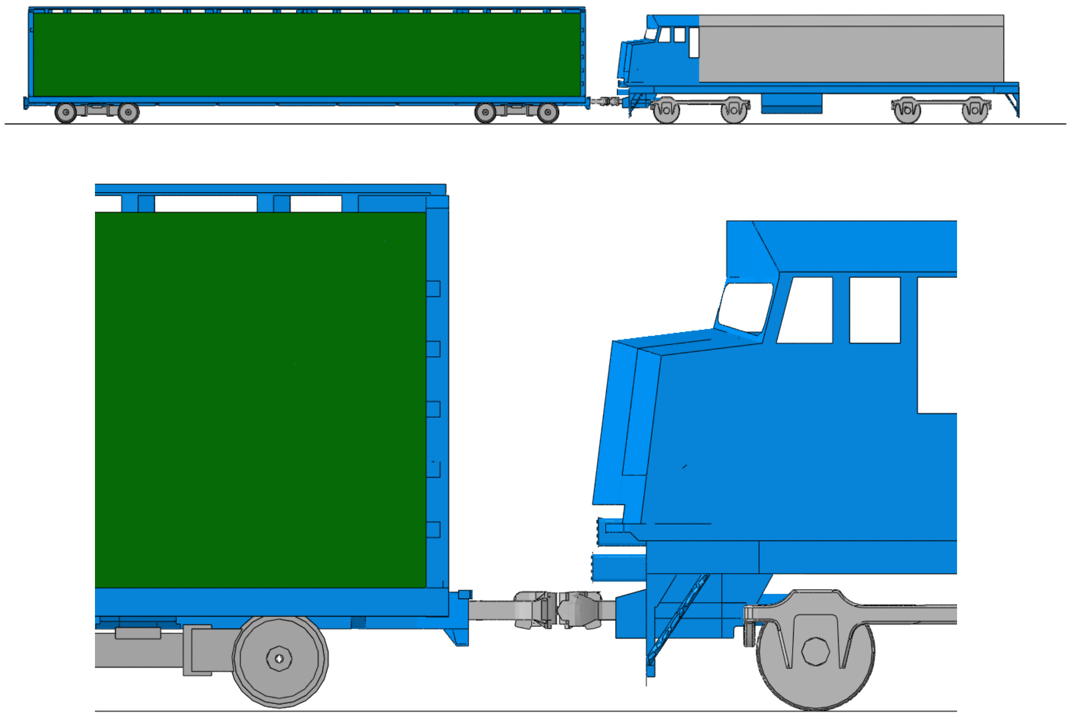


Figure 44. Side views of the locomotive-into-freight car FE model in the undeformed configuration (baseline case: vehicles aligned): above—entire two-vehicle model; below—detail of colliding interface

An annotated force-displacement curve for the baseline case is shown in Figure 45. The first 35 or so inches of vehicle crush were dominated by the push-back of the couplers, first the freight car cushion unit, which had been defined to push back at a load of 600,000 lbf, and then the modified locomotive PBC, which pushed back at a load of 674,000 lbf.

As was the case for the modified MP40 locomotive, the bolts broke at approximately 36 inches of crush, and for the next 16 inches or so of relative vehicle displacement, there was no further contact between the vehicles. At 52 inches of crush, the DAC impacted the front wall of the freight car and began to crush.

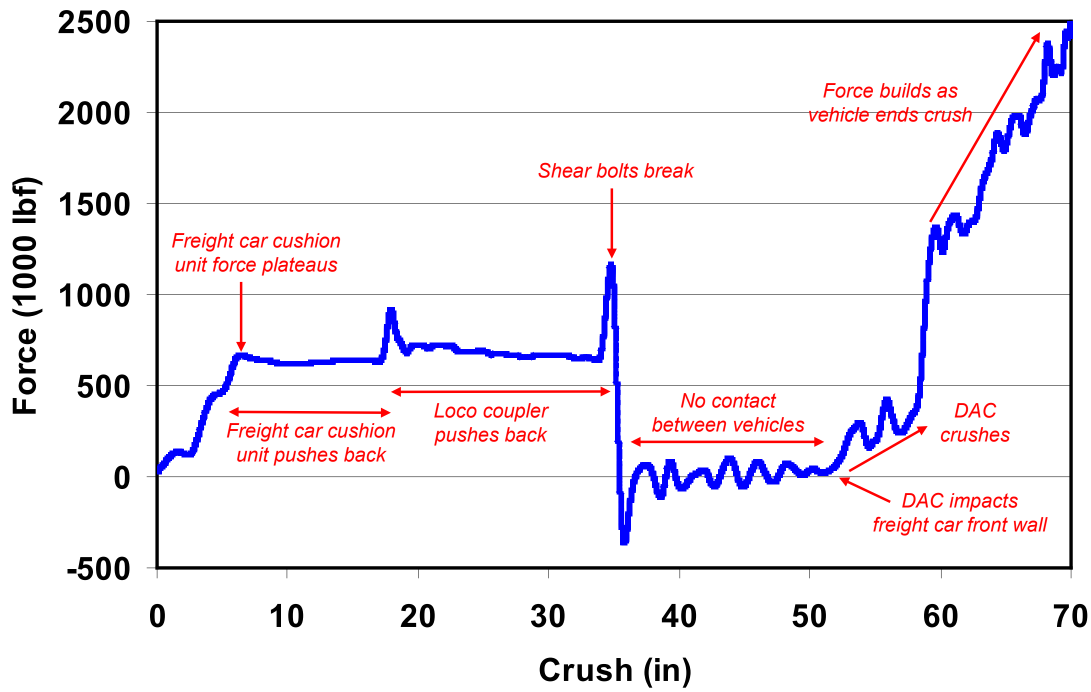


Figure 45. Collision of the modified locomotive into a freight car: annotated force vs. displacement curve

Figure 46 shows a side view of the colliding interface at a crush level of 69 inches. The vehicle ends were completely engaged at this point. Isometric views of each vehicle are shown in Figure 47. The DAC tubes crushed extensively, as did the front wall of the freight car and the short hood of the modified locomotive. As is evident in Figure 47, the stiff center beam of the freight car caused the plate connecting the upper DAC tubes to bend back extensively.

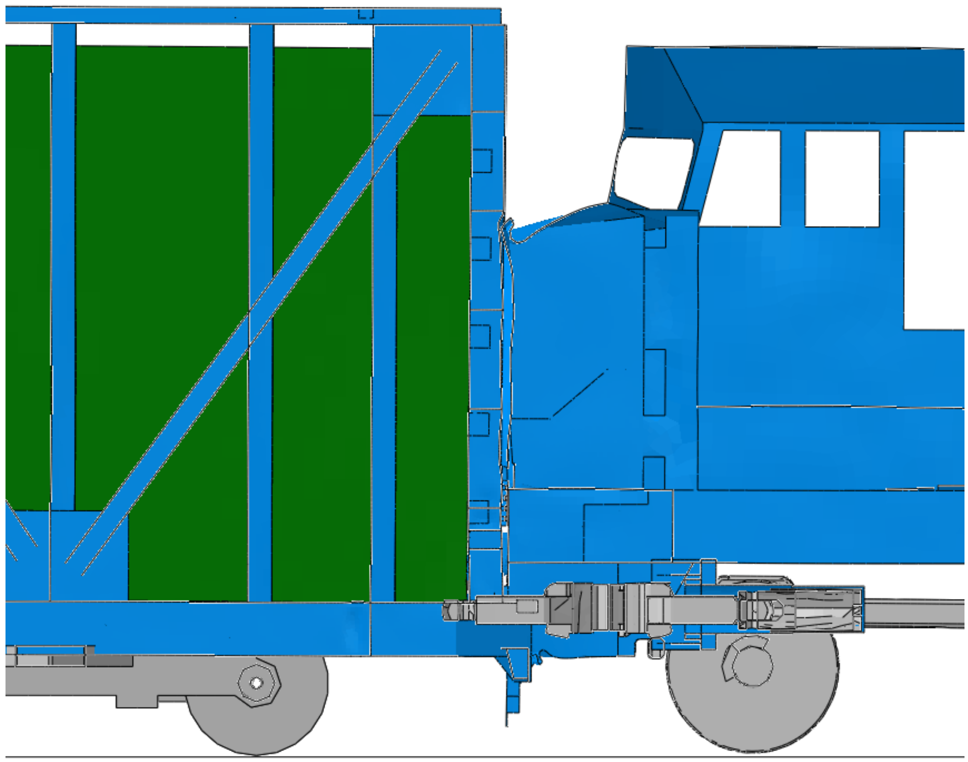


Figure 46. Collision of the modified locomotive into a freight car (baseline case: vehicles aligned): side view of colliding interface after approximately 69 inches of crush

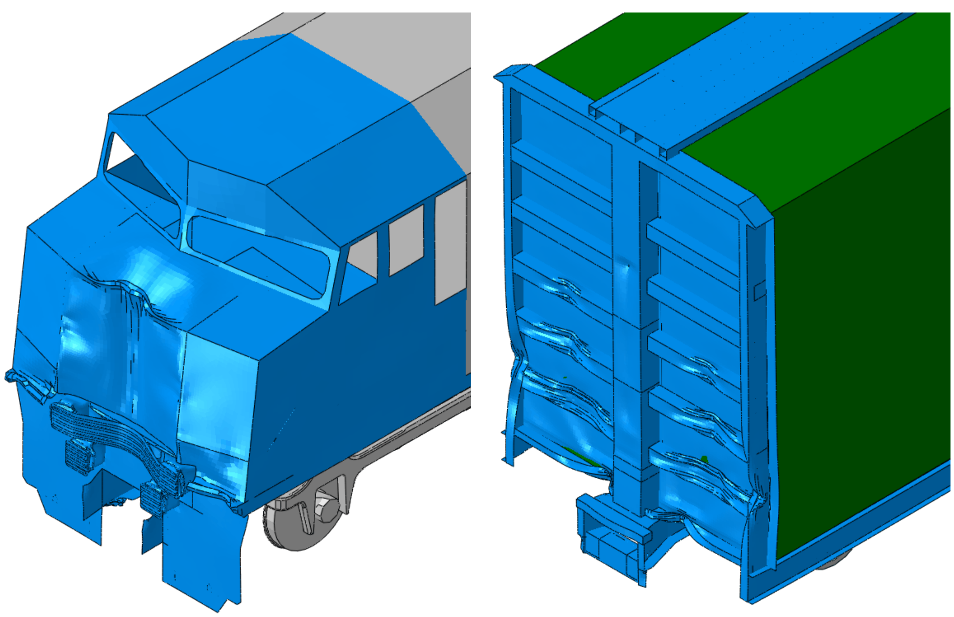


Figure 47. Collision of the modified locomotive into a freight car (baseline case: vehicles aligned): isometric views showing the front ends of: left—the modified locomotive; and right—the freight car after 69 inches of crush

In addition to the baseline case in which the two vehicles were aligned, collisions were simulated in which the vehicles were offset by 3 inches both laterally and vertically, with the conventional locomotive raised by 3 inches in one case and lowered by 3 inches in another case (and offset to the right as viewed from the engineer's position in the cab in both cases). These analyses were conducted for the same collision speed that was used in the baseline analysis. A comparison of the force-displacement curves for these three cases are shown in Figure 48. As is evident, the load was different in the 52 inches to 60 inches crush range for the offset cases. This was likely because the stiff center beam was closer to one of the upper crush tubes and loaded it more severely. Also, when the freight car was lowered by 3 inches, it appeared that the peak load decreased. This was likely due to the decreased resistance of the front wall of the flat car when impacted at a higher point.

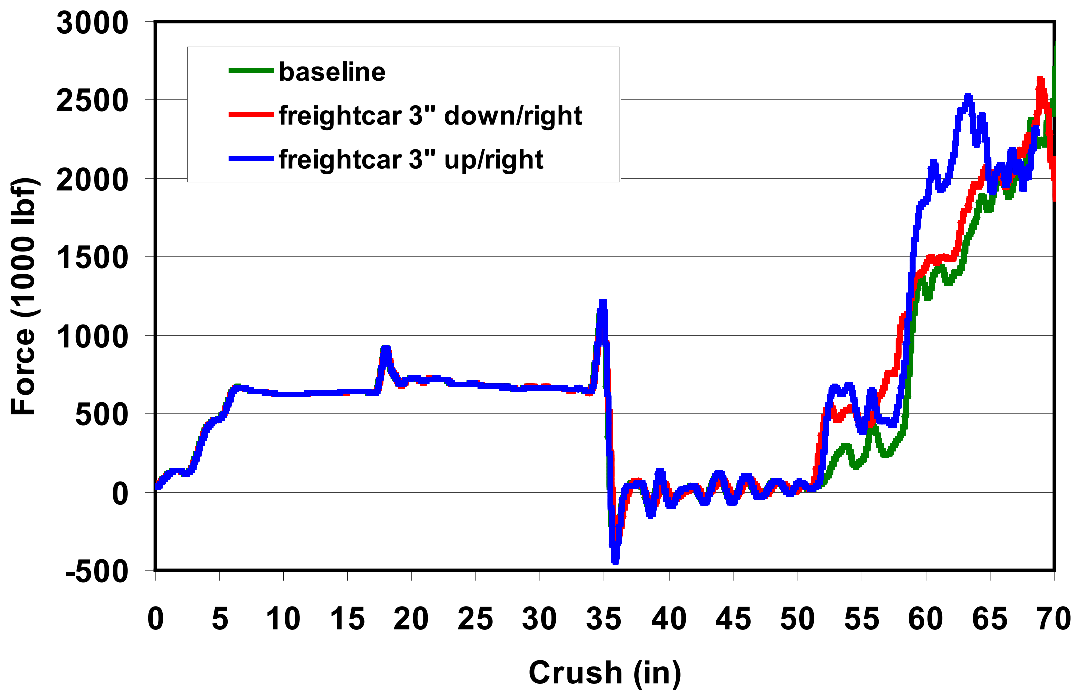


Figure 48. Collision of the modified locomotive with a freight car: comparison of force-displacement curves for in-line and offset cases

Table 4 summarizes energy absorption levels for the three modified locomotive-into-freight car collision cases. The calculated peak wheel lift in the respective forward trucks is also listed in this table. This collision was different than the others because the freight car cushion unit absorbed a considerable amount of energy and because the DAC did not interact with the freight car until the vehicle-vehicle crush level had reached 52 inches. Nonetheless, the energy absorption achieved in the DAC system reached 640 ft-kips for the baseline case, satisfying requirements, and was over 3 million ft-lbf in total.

Table 4. Collision of the modified locomotive with a freight car: comparison of energy absorption levels (in ft-kips) and peak wheel lift at a crush level of 69 inches

	Baseline (In-Line)	Freight Car Shifted 3" Up/Right	Freight Car Shifted 3" Down/Right
Locomotive Push-back Coupler	1,100	1,100	1,100
Freight Car Cushion Unit	590	590	590
Deformable Anti-climber	640	690	680
Other Modified Locomotive Structures	340	540	540
Freight Car Structures	570	620	480
Total	3240	3540	3390
Wheel Lift (Locomotive)	0.9"	1.3"	1.2"
Wheel Lift (Freight Car)	< 0.1"	< 0.1"	< 0.1"

6. Drawing and Construction Sequence

Once it was determined that the design for the F40 retrofit satisfied requirements, Canarail developed mechanical drawings for fabrication of the two modified crashworthy components, fabrication of reinforcements to the F40 locomotive, and for installation of the components and reinforcements onto the F40 test vehicle at the TTC.

A drawing tree for the set of drawings that were produced is listed in Appendix A. The hierarchy of the drawing tree features five "tiers."

At the top level "tier 1" there are two "preparation" drawings — "Modification Locomotive 234" (14424-0001) and "Locomotive 234 Cutting Arrangement" (14424-0002). These drawings describe the procedure for preparing locomotive 234 so that it could be modified with reinforcements and installation of the two crashworthy components. Drawing 14424-0001 is shown as an example in Figure 49.

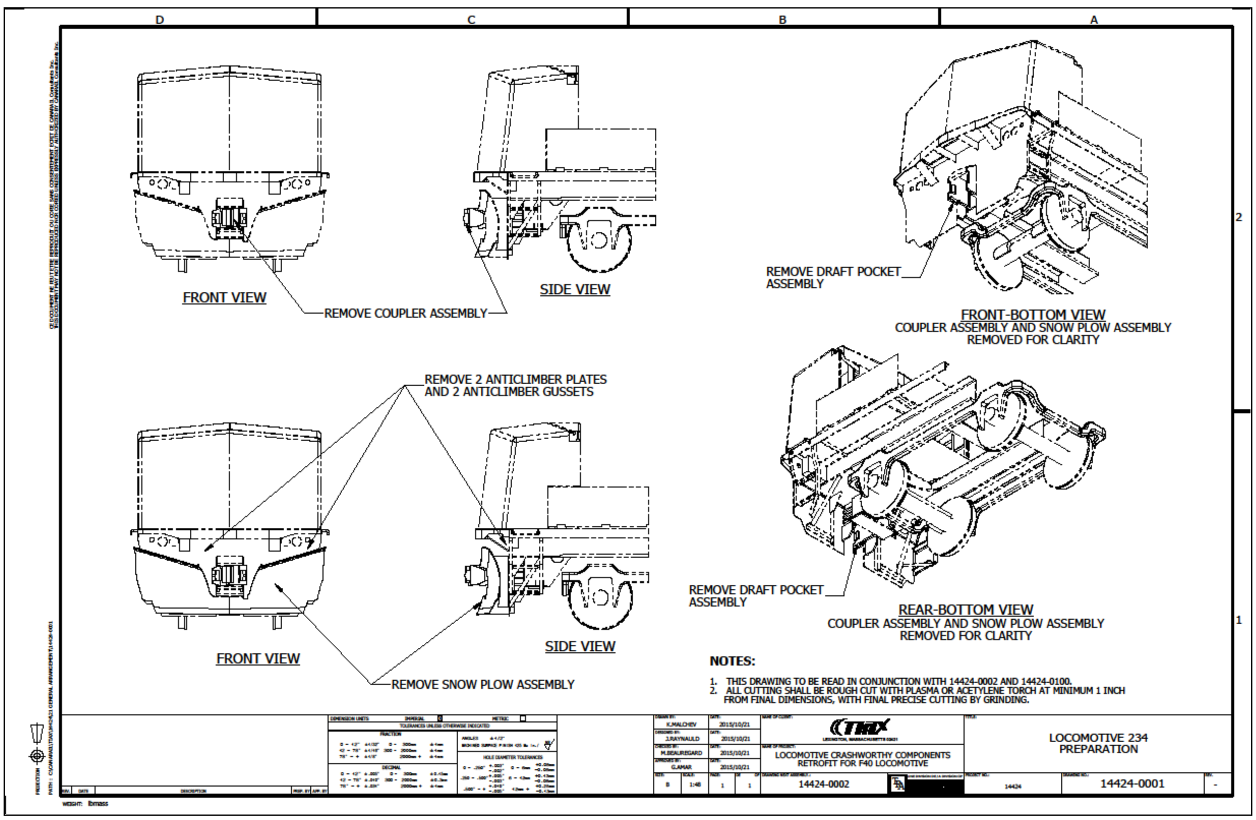


Figure 49. Drawing 14424-0001: "Modification Locomotive 234" describes preparation of the locomotive for installation of reinforcements and the two crashworthy components

The package includes six "tier 2" installation-level sets of drawings, each with a set of tier 3, tier 4 or tier 5 sub-level drawings:

- Installation Reinforcement (14424-0100) with 14 sub-level drawings
- Installation PBC Pocket & Sliding Lug (14424-0200) with 19 sub-level drawings

- Installation DAC Top (14424-0400) with 8 sub-level drawings
- Installation DAC Bottom (14424-0500) with 7 sub-level drawings
- Coupler and Carrier Installation (14424-0600) with 12 sub-level drawings (10 of which are 14424-03xx drawings_
- Installation Closure Plate (14424-0700) with 1 sub-level drawing.

This drawing package was reviewed by two individuals at TIAX: Scott Ballard, a metal fabrication and welding specialist, who has over 35 years of experience in this area, and David Nedder, the lead CAD engineer, who has over 30 years of experience in computer-aided design and also has several years of experience as a metal fabricator. Based on their review, they identified several issues in the drawing package that required modification. These were delivered to Canarail, who modified the design and associated drawings accordingly.

Draft and final drawing packages were delivered electronically to the Volpe Center in .pdf format.

7. Summary and Conclusions

The results of the FE analyses presented in Section 5 confirm that the modified design for the retrofit of the two crashworthy components meets the specified requirements. FE analyses indicated that both crashworthy components performed effectively in all of the collision scenarios. Required energy absorption levels were met in all but one offset case for one collision scenario—a collision between a modified locomotive and a cab car for which the cab car was lowered by 3 inches and shifted laterally by 3 inches. For this case, the energy absorption of the DAC reached only 430 ft-kips before the draft sill of the cab car began to buckle, and once the buckling commenced, most of the subsequent deformation occurred in the cab car. In spite of this low energy absorption value for the DAC, the total energy absorption for this scenario was still over 2 million ft-lbf, and the end frames of the modified locomotive and the cab car engaged extensively, indicating that override of one vehicle onto the other was unlikely.

Table 5 through Table 9 further illustrate how the modified design for retrofit of the two crashworthy components into an F40 locomotive satisfied the requirements outlined in Section 3 of this report. The information reported in these tables was very similar to what was reported in a series of tables in the report describing the prior locomotive crashworthy components development program [1]. By and large, the outcome of the evaluation was unchanged. Key differences are noted in the comments or footnotes of the respective tables.

Table 5. Satisfaction of performance requirements—push-back coupler

REQUIREMENT	THRESHOLD	MET?	DEMONSTRATED HOW?	COMMENTS
Trigger mechanism	Shear bolt or deformation tube	Yes	By design	
Trigger load	Min–600,000 lbf; max–800,000 lbf	Yes	Testing/FEA	Previously confirmed in tests
Enables end frames to engage		Yes	FEA	
Stroke	Min–enough to capture couplers; max–open space behind draft gear	Yes	By design; examination of existing locomotives	
Energy absorption	Controlled during pushback; min–600,000 ft-lbf	Yes	Testing/FEA	Previously confirmed in tests
Support structure strength	No permanent deformation prior to PBC exhaustion; crippling load not exceeded in 12 mph collision.	Yes	FEA/1-D dynamic analysis (CEM consist)	Coupler stroke of only 13 inches predicted for CEM consist impact scenario.
Torsional resistance	Min–150,000 ft-lbf prior to push-back and after exhaustion	Yes	Coupler design calculations (prior to push-back)	After exhaustion, end frames were engaged; huge torsional resistance.
Strength in draft	Min–150,000 lbf at any point during push-back	Yes	Coupler design calculations	Previously evaluated
Material failure	No failure (material separation)	Yes	FEA/Testing	Previously confirmed in tests

Table 6. Satisfaction of performance requirements—DAC

REQUIREMENT	THRESHOLD	MET?	DEMONSTRATED HOW?	COMMENTS
Trigger mechanism	Plastic deformation/progressive buckling of energy absorbers	Yes	By design/FEA	
Stroke	Min–10 inches	Yes	FEA	Predicted stroke of DAC was ~15 inches prior to consolidation.
Energy absorption	Min–600,000 ft-lbf	Yes/no	FEA	See footnote.*
Vertical strength	Min–100,000 lbf	Yes	FEA	FEA results indicated that vertical load capacity was more than 300,000 lbf .
Support structure strength	Strong enough to support crush loads without failing or undergoing large plastic deformation; crippling load not exceeded in 12 mph collision.	Yes	FEA/1-D dynamic analysis (CEM consist)	Coupler stroke of only 13 inches predicted for CEM consist impact scenario, so no DAC impact in 12 mph collision.
Material failure	No failure (material separation)	Yes	FEA/Testing	Subcomponent and component tests were planned.

* Note: The energy absorption requirement was met for all of the cases except for the locomotive-to-cab car collision scenario—the case in which the cab car was lowered and moved to the right by 3 inches with respect to the modified locomotive (430 ft-kips). Note that, although this requirement was not met, the overall energy absorption of the vehicle end structures was sizable (see Table 3 and Table 4).

Table 7. Satisfaction of performance requirements—collision scenarios

REQUIREMENT	MET?	DEMONSTRATED HOW?	COMMENTS
No override of one vehicle onto another	Yes	FEA	FEA indicated that end structures lock together in all collision scenarios.
No formation of a ramp that might eventually lead to override.	Yes	FEA	
No uncontrolled deformation in modified locomotive	Yes	FEA	No significant drop-off in load through 45" of crush
No uncontrolled deformation in conventional vehicles	Yes	FEA	Cab car draft sill began to buckle only after 40" of crush; freight car underframe began to buckle only after 70" inches of crush.
A best-fit straight line approximation of the force/crush data shall exhibit a positive slope until the crush for the crashworthy components is exhausted and the underframe begins to crush.	Yes/No	FEA/Force-displacement curve analysis	See footnote.*
The strength of the underframe shall be at least 50% higher than the average crush strength of the combined DAC/PBC system.	Yes	FEA	
The underframe must be strong enough to support the loads on the DAC and PBC without undergoing large deformation.	Yes	FEA	

* A best-fit straight line through the each of the complete force-crush curves exhibited a positive slope for all load cases; however:

- For the all of the locomotive-to-freight car load cases there were some points along the load-crush curve at which a best-fit straight line that stops at that point will have a negative slope. This occurred because the load following shear bolt failure dropped significantly for these cases (effectively to zero for the locomotive-to-freight car load cases).
- For all of the locomotive-to-locomotive load cases there were some points along the load-crush curve at which a best-fit straight line that stops at that point will have a slope that is near zero and may, in fact, become slightly negative. This also occurred because the load following shear bolt failure dropped for these cases (not to near-zero, as it did for the locomotive-to-freight car cases, but still by a significant amount).

Despite these brief occurrences of negative slopes for the best-fit lines, the research team believed that the negative slops arose because of the change in load path, and were not representative of an instability in the crush behavior.

Table 8. Satisfaction of geometric requirements

REQUIREMENT	MET?	DEMONSTRATED HOW?	COMMENTS
Push-back coupler cannot interfere with existing locomotive structures during and following push-back to its complete stroke.	Yes	By design; examination of existing locomotives	Examination of the F40 locomotive indicated that clearance is tight behind the draft gear, as noted in Section 2.
Deformable anti-climber—width: Must extend laterally, at a minimum, to the approximate 1/3 points across the width of the end of the locomotive; must also extend laterally to the main longitudinal beams of the locomotive	Yes	By design	
Deformable anti-climber—depth: Center must extend to within 4 inches of the pulling face of the coupler with the draft gear fully compressed and must extend no less than 10" from the locomotive front plate for its required width	Yes	By design	
Deformable anti-climber—Cannot interfere with other equipment, unless it is agreed that such equipment can be easily re-routed.	Yes	By design	Design may require minor re-routing of cabling.

Table 9. Satisfaction of operational requirements

REQUIREMENT	MET?	DEMONSTRATED HOW?	COMMENTS
Low-speed coupling—The PBC system must be able to withstand a hard couple between two locomotives at a speed of 5 mph without triggering the push-back system.	Yes	Coupler design calculations, FEA	No permanent deformation in PBC for 5 mph locomotive-locomotive collision
Curving—The components of the locomotive shall not interfere for operation with nominally identical vehicles operating on curves up to 23 degrees.	Yes	By design	DAC components positioned within envelope of conventional locomotive skirt.

Table 10. Satisfaction of fabrication requirements

REQUIREMENT	MET?	DEMONSTRATED HOW?	COMMENTS
General—The design should utilize materials and fabrication methods that a normal metal fabrication company could use.	Yes	By design	
Materials—Materials of construction for the primary structure and the energy absorbing elements shall be either high strength low alloy or austenitic stainless steels.	Yes	By design	All materials specified as A572-50
Construction methods—All primary structural members shall be welded in accordance with AWS D15.1. Bolting may be used for the PBC trigger mechanism.	Yes	By design	AWS D15.1 called out in all drawings that include welding
Deformable anti-climber—the PBC and DAC components shall be designed so that they can be integrated onto an existing passenger locomotive.	Yes	By design	Integration requires replacement of draft pocket, minor modification to front plate; some cable rerouting; addition of some support structure.

As FRA and Volpe proceed with the vehicle-to-vehicle impact testing phase of this research, there are a few key aspects of the design that must be considered:

- There was clearly very little expected clearance between the deformation tube of the PBC and the front axle/traction motor bracket of the forward truck. While the push-back-coupler had been removed from the load path by the time these components came close to one another, the potential for interference in certain circumstances was not negligible.
- The coupler shank that was available for use with its PBC was 31 inches in length, 2.5 inches longer than the 28.5-inch standard for the F40 locomotive. Analysis results indicated that the longer coupler shank length had no bearing on the results of the analyses other than that it provided 2.5 inches more stroke to the PBC before the DACs were impacted in any of the scenarios. In fact, it provided 160 ft-kips of energy absorption in the PBC but had little or no other effect on collision behavior.
- The FE model used material properties based on measurements for the A572-50 materials used to reinforce the modified locomotive. Measured properties were not available for the A36 material found in much of the F40 locomotive or the RY306 steel used in the end frame of the cab car. Based on experience gained in the earlier crashworthy locomotive components program, the measured properties could be 20 percent to 30 percent higher than the reported properties, which were viewed as minima by steel manufacturers. FE model predictions must be viewed with these limitations in mind. However, it was noted that, since the measured properties of A36 and RY306 would almost certainly be higher than those used in the models, it was likely that the energy absorption levels in the DAC would be greater if measured properties for these materials were used, because the other structures would be more resistant to crush.

Overall, FRA and Volpe were confident that the crashworthy locomotive components could be successfully retrofitted onto the F40 test locomotive and behave in a predictable manner in any of the vehicle-to-vehicle tests evaluated.

8. References

1. Federal Railroad Administration. (2014). Development, Fabrication and Testing of Locomotive Crashworthy Components: Base Effort [DOT/FRA/ORD-14/38]. Washington, DC: U.S. Department of Transportation.
2. TIAX LLC. (2009). Development and Fabrication of State-of-the-Art End Structures for Budd M1 Cars. TIAX Final Report to Volpe Center, contract DTRS57-04-D-30008 (TO #7).
3. Tyrell, D., Severson, K., Marquis, B., Martinez, E., Mayville, R., Rancatore, R., Stringfellow, R., Hammond, R., and Perlman, A.B. (1999). Locomotive Crashworthiness Design Modifications Study. *Proceedings of the 1999 IEEE/ASME Joint Railroad Conference.* Institute of Electrical and Electronics Engineers.
4. Federal Railroad Administration (2003). Crashworthiness Design Modifications for Locomotive and Cab Car Anticlimbing Systems [DOT/FRA/ORD-03/05]. Washington, DC: U.S. Department of Transportation.
5. Federal Railroad Administration. (2003). Passenger Rail Train-to-Train Impact Test. Volume 1: Overview and Selected Results [DOT/FRA/ORD-03/17.1]. Washington, DC: U.S. Department of Transportation.
6. American Public Transportation Association. (2006). APTA SS-C&S-034-99, Rev. 2, Standard for the Design and Construction of Passenger Railroad Rolling Stock.
7. Association of American Railroads. (2008). AAR S-580 Standard, Locomotive Crashworthiness Requirements," adopted December 2004, revised 2008.
8. Code of Federal Regulations. Title 49, Part 229, Railroad Locomotive Safety Standards.
9. American Public Transportation Association. (2012). APTA RP-C&S-019-11, Recommended Practice for Pushback Couplers in Passenger Rail Equipment.
10. SolidWorks Software.
11. Abaqus CAE Software.
12. Abaqus Explicit Software.

Appendix A.
Drawing Record

14-424 Crashworthy F40

DRAWING RECORD

REVISION: D

DATE: 11/18/2015

Line #	REV	DWG #	tier 1 (Preparation)	tier 2 (Installation)	tier 3 (Assembly weldment)	tier 4 (Sub-assy Sub-)	tier 5 (Detail)	Drawing Title	comment
1	-	14424-0001	X					LOCOMOTIVE 234 PREPARATION	
2	A	14424-0002	X					LOCOMOTIVE 234 CUTTING ARRANGEMENT	
3									
4	**A**	**14424-0100**		X				**INSTALLATION REINFORCEMENT**	
5	-	14424-0101					X	STIFFENING LONGITUDINAL ANGLE	
6	-	14424-0102					X	STIFFENING VERTICAL PLATE	
7	-	14424-0103					X	STIFFENING SIDE BACKING BAR	
8	-	14424-0104					X	STIFFENING CENTRAL BACKING BAR	
9	-	14424-0105					X	STIFFENING SIDE FRONT PLATE	
10	-	14424-0106					X	STIFFENING CENTRAL FRONT PLATE	
11	-	14424-0107					X	COLLISION POST NEW FRONT FLANGE	
12	A	14424-0108					X	CLOSURE SHEET SIDE BACK	
13	-	14424-0109					X	CLOSURE SHEET CENTRAL BACK	
14	-	14424-0110					x	STIFFENING VERTICAL BACKING BAR	
15	-	14424-0120				X		WELDMENT STIFFENING PLATE	
16	-	14424-0121					X	STIFFENING HORIZONTAL PLATE	
17	-	14424-0122					X	STIFFENING FRONT BACKING PLATE	
18	-	14424-0130				X		WELDMENT STIFFENING PLATE	
19									
20	**A**	**14424-0200**		X				**INSTALLATION PBC POCKET & SLIDING LUG**	**TC09016-0023**
21	A	14424-0210			X			PBC COUPLER POCKET ASSEMBLY	TC09016-0025/TC09016-0026
22	A	14424-0211					X	SIDE STIFFENER-BOTTOM	TC09016-0040/TC09016-0049
23	A	14424-0212					X	SIDE STIFFENER-MIDDLE	TC09016-0039
24	A	14424-0213					X	SIDE STIFFENER-TOP	TC09016-0038
25	A	14424-0214					X	PBC-BACKING BRACKET	
26	-	14424-0215					X	SIDE WALL	TC09016-0036
27	-	14424-0216					X	PBC BUFF LUG	TC09016-0037
28	-	14424-0217					X	PBC ANGLED PLATE	TC09016-0045
29	-	14424-0218					X	PBC-SIDE PLATE 3	
30	A	14424-0219					X	PBC-LEFT BACK BRACKET	
31	A	14424-0220					X	PBC-RIGHT BACK BRACKET	
32	-	14424-0221					X	RAIL STOPPER	TC09016-0047
33	B	14424-0222					X	CARRIER SUPPORT	
34	-	14424-0223					X	STOPPER PLATE	TC09016-0050
35	-								
36	-	14424-0230			X			PBC SLIDING LUG ASSEMBLY	TC09016-0027
37	-	14424-0231					X	BACK PLATE	TC09016-0041
38	-	14424-0232					X	SIDE PLATE-RHS	TC09016-0051
39	-	14424-0233					X	GUSSET	TC09016-0043
40	-	14424-0234					X	SIDE PLATE-LHS	TC09016-0042
41	-	14424-0235					X	TOP AND BOTTOM GUSSET	TC09016-0048
42									
44	-	14424-0310				X		COUPLER CARRIER ASSEMBLY TOP	
45	-	14424-0311					X	TOP COVER SIDE WALL	
46	-	14424-0312					X	TOP COVER FRONT WALL	
47	-	14424-0313					X	TOP COVER PLATE	
48	-	14424-0314					x	COUPLER CARRIER THREADED BLOCK	
49	A	14424-0320				X		COUPLER CARRIER ASSEMBLY BOTTOM	
50	-	14424-0321					X	BOTTOM CHANNEL	
51	-	14424-0322					X	SIDE ANGLE	
52	A	14424-0323					X	SIDE PLATE	
53	-	14424-0324					X	COUPLER CARRIER CYLINDER	
54									
55	**A**	**14424-0400**		X				**INSTALLATION DAC TOP**	**TC09016-0005/TC09016-0012**
56	-	14424-0401					X	REINFORCEMENT PLATE	TC09016-0014
57	-	14424-0402					X	REINFORCEMENT PLATE	TC09016-0019
58	-	14424-0410				X		FRONT PLATE ASSEMBLY	
59	-	14424-0411					X	TOP ANTI-CLIMBER PLATE	TC09016-0009
60	-	14424-0412					X	LONG RECTANGULAR STEEL BAR	TC09016-0015
61	-	14424-0420				X		TUBE ASSEMBLY	
62	-	14424-0421					X	HALF CRUSH TUBE WITH GROOVE	TC09016-0006
63	-	14424-0422					X	CERAMIC BACKING BAR	
64									
65	-	**14424-0500**		X				**INSTALLATION DAC BOTTOM**	**TC09016-0012**
66	-	14424-0510			X			DAC BOTTOM ASSEMBLY	TC09016-0056
67	-	14424-0520				X		FRONT PLATE ASSEMBLY	
68	-	14424-0521					X	BOTTOM ANTI-CLIMBER PLATE	TC09016-0011
69	-	14424-0522					X	SHORT RECTANGULAR STEEL BAR	TC09016-0017
70	-	14424-0530				X		TUBE ASSEMBLY	
71	-	14424-0531					X	CERAMIC BACKING BAR	
72	-	14424-0532					X	HALF CRUSH TUBE WITH GROOVE	TC09016-0058
75									
76	**A**	**14424-0600**		X				**COUPLER AND CARRIER INSTALLATION**	
77	-	14424-0610			X			PBC ASSEMBLY	
78	A	14424-0630				X		COUPLER CARRIER ASSEMBLY - CAB END	
79									
80	**A**	**14424-0700**		X				**INSTALLATION CLOSURE PLATE**	
81	A	14424-0701					X	CLOSURE SHEET U-SHAPED	

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
E	Elastic Modulus
CFR	Code of Federal Regulations
CEM	Crash Energy Management
CG	Center of Gravity
FRA	Federal Railroad Administration
FEA	Finite Element Analysis
TTC	Transportation Technology Center (the site)
TTCI	Transportation Technology Center, Inc. (the company)
S_U	Ultimate Strength
S_Y	Yield Strength