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Conventional and Crash Energy Management Locomotive Coupling Tests

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13. ABSTRACT (Maximum 200 words) Crash energy management (CEM) components which can be integrated into the end structure of a locomotive were developed: a push-back coupler (PBC) and a deformable anti-climber (DAC). These components are designed to inhibit override in the event of a collision. The results of vehicle-to-vehicle override, where the strong underframe of one vehicle, typically a locomotive, impacts the weaker superstructure of the other vehicle, can be devastating. These components are designed to improve crashworthiness for equipped locomotives in a wide range of potential collisions, including collisions with conventional locomotives, conventional cab cars, and freight equipment. Concerns have been raised in discussions with industry that PBCs may trigger prematurely, and may require replacement due to unintentional activation as a result of service loads. PBCs are designed with trigger loads greater than the expected maximum service loads experienced by conventional couplers. Two sets of coupling tests were conducted to demonstrate this, one with a conventional locomotive, and another with a conventional locomotive retrofit with a PBC. These tests allowed a performance comparison of a conventional locomotive with a CEM-equipped locomotive during coupling. Test results demonstrate that PBCs will not trigger at typical coupling speeds, and will trigger at the proper force level.			
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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

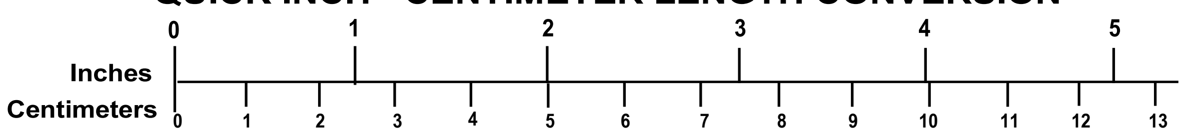
VOLUME (APPROXIMATE)

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)

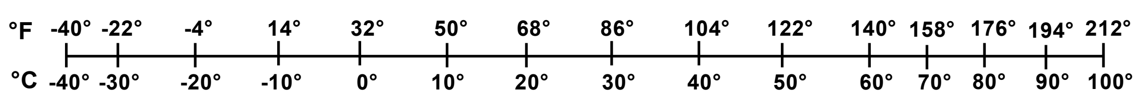
TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



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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Executive Summary

The Volpe Center conducted locomotive crashworthiness coupling tests in support of the locomotive crashworthiness program of the Federal Railroad Administration (FRA) Office of Research, Development and Technology. Analysis, fabrication, testing were conducted from August 2014 to November 2018. The first set of tests consisted of coupling tests of a conventional F40 locomotive coupling with a Budd M1 cab car (M1). The second set of tests comprised coupling tests of an F40 retrofit with a crash energy management (CEM) system coupling with an M1 cab car. The CEM system is comprised of a push-back coupler (PBC) and a deformable anti-climber (DAC).

Industry has raised concerns that PBCs may trigger prematurely, and may require replacement due to unintentional activation as a result of service loads. Push-back couplers are designed with trigger loads greater than the expected maximum service loads experienced by conventional couplers. Analytical models are typically used to determine these required trigger loads. Researchers conducted two sets of coupling tests to demonstrate this, one with a conventional locomotive equipped with conventional draft gear and coupler and another with a conventional locomotive retrofit with a PBC.

The conventional coupling tests established a baseline for comparison with the CEM coupling tests. The objective of the conventional coupling tests was to measure and characterize the structural performance of the conventional coupler and the coupling vehicles under a range of increasing dynamic coupling speeds to determine when damage occurred in the coupler system. Volpe Center researchers conducted computer simulations of the impacts prior to the tests and served to inform the testing decisions. In the tests, equipment damage began at 6 mph. Computer simulations predicted that damage would occur for coupling speeds between 6 and 8 mph. The test results compared favorably with the pre-test predictions and confirmed that coupling speeds should be kept below 6 mph to prevent equipment damage.

After the conventional coupling tests, Volpe retrofit a CEM system onto an F40 locomotive and a series of dynamic CEM coupling tests were conducted. The primary objective was to demonstrate the robustness of the PBC design and determine the impact speed at which PBC triggering occurs. The test objective was to measure and characterize the structural performance of the PBC and the coupling vehicles under a range of increasing dynamic coupling speeds until damage occurred in the coupler system. The test results compared favorably with the pre-test predictions for the coupling force at impact. Additionally, the pre-test modeling predicted that damage would occur in the M1 truck-to-carbody connection at speeds above 5 mph. This was confirmed in the tests.

The CEM coupling tests also successfully demonstrated the force level at which the PBC is designed to trigger. In the test, the PBC triggered at just under 9 mph. With corrected masses and the idealized PBC characteristic updated after the test, a post-test collision dynamics model estimated that the PBC triggered between 8 and 9 mph. The CEM coupling tests showed that for the given vehicle-to-vehicle coupling scenario, it is unlikely that the PBC will trigger within the common coupling speed range during typical operation.

Certain aspects of the strain gage data were analyzed. The Volpe Center found that the force through the two coupler locations were remarkably consistent with one another and indicated an

effectively linear increase in coupler force with impact speed. For lower coupling speeds, these strain gage-based estimates of force were also consistent with acceleration-based estimates of force. For higher coupling speeds, the agreement was not as good, likely because the dynamics of the impact at these higher speeds did not lend themselves to estimates that assumed the entire mass of the vehicle was decelerating uniformly.

The research team compared the test results for the conventional coupling tests with those of the CEM coupling tests. The relationships between impact force and impact speed for both series of tests were almost identical for impact speeds of less than 6 mph. However, the results diverged at impact speeds greater than 6 mph. This was due to the draft gear system of the PBC on the CEM locomotive. The draft gear effectively limited the impact load until the PBC was triggered at 9 mph.

The results showed that the PBC behaved very much like the conventional coupler for the complete range of typical coupling speeds. The triggering of the PBC occurred at a speed much greater than the maximum coupling speed recommended by the Association of American Railroads, 4 mph. Additionally, the likelihood of coupling was lower at the higher coupling speeds. Computer models can be used to extrapolate and determine coupling speeds for other coupling scenarios. Most PBC manufacturers utilize modeling and testing to design and ensure their PBC will not trigger in coupling scenarios defined by the purchaser. Additionally, the draft gear components of the PBC can be designed to have a higher elastic capacity for cushioning higher-speed coupling events to protect the PBC from premature activation.

The conventional and CEM coupling test results both compared favorably with the analyses. Additional full-scale dynamic tests are planned which will accomplish the objectives of demonstrating that the locomotive CEM system performs well in service, provides crashworthiness compatibility with a range of equipment, and exhibits increased crashworthiness over conventional equipment. The information and experience gained from analyzing and conducting the conventional and CEM coupling tests provided the foundation for conducting the planned vehicle-to-vehicle tests and the train-to-train tests.

1. Introduction

The Federal Railroad Administration (FRA) Office of Research, Development and Technology is directing research to develop new technologies for increasing the safety of passengers and crew in rail equipment. Much of this work has focused on mitigating the consequences of train-to-train collisions. Locomotive crashworthiness research is being conducted as part of the FRA program. The approach of the program is to review relevant accidents and identify structural candidates for design modifications. Analytical tools and testing techniques are used to evaluate the effectiveness of these design alternatives. The crashworthiness research approach begins with developing a baseline measure of existing design performance for a given scenario and extends to developing improvements for enhancing safety performance for that scenario. The current stage of research is focused on evaluating locomotive crashworthy component designs under dynamic impacts.

1.1 Background

In the event of a 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 vehicles onto the other. Locomotives, because of their great longitudinal strength and stiffness, are particularly susceptible to override when they collide with another vehicle, the consequences of which can be catastrophic. Research has shown that conventional anti-climbing structures can deform on impact and form a ramp, increasing the likelihood of override [1]. 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 23-mph collision that occurred in Red Oak, Iowa on April 17, 2011 [2].

As seen in Figure 1, the accident resulted in several maintenance-of-way equipment cars overriding the impacting locomotive. The photograph shows the impacting locomotive's modular crew cab was detached and partially crushed as a result of being overridden, resulting in two fatalities. To be effective, an anti-climber must engage the end structures of opposing equipment and provide sufficient vertical load-carrying capacity to prevent such override.

Figure 1. Red Oak, Iowa collision, April 17, 2011

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

1. Push-back couplers (PBCs)
2. Deformable anti-climbers (DACs)

Push-back couplers allow the ends of the vehicles to engage prior to the build-up of large forces and moments that might lead to lateral buckling or vertical climb of the vehicles with respect to one another. Deformable anti-climbers provide sufficient vertical load-carrying capacity as they deform gracefully and predictably, conforming to the shape of the adjacent vehicle to prevent the formation of a ramp. Crushable zones just behind the anti-climber face absorb collision energy as they collapse, preventing uncontrolled deformation of structural features that might cause formation of a ramp. The events that can lead to override are minimized when the push-back coupler and deformable anti-climber are used in tandem.

Structural features such as these that are specifically put in place to mitigate the effects of a collision are common in rail vehicles that are 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.

The Volpe National Transportation Systems Center (Volpe Center) is supporting the FRA Office of Research and Development in the development of a CEM system for locomotives. In a previous research program, the Volpe Center developed several concepts for a more crashworthy locomotive [3]. The study addressed the feasibility of incorporating PBCs and DACs into locomotives. Conceptual design goals included the preservation of occupant volume and the maintenance of vehicle-rail contact, i.e., the prevention of override, while ensuring that the equipment was compatible with existing operating requirements. Building on this previous work, the objectives of the recently completed research program were to: (1) develop detailed designs for a push-back coupler and a deformable anti-climber; (2) develop test article designs for the components; (3) fabricate the test articles; (4) conduct the component tests; and, (5) if necessary, refine the designs based on the results of the tests.

The development of the component designs is detailed in an ASME paper [4]. The finite element analyses of the component designs are detailed in a second ASME paper [5]. A third ASME paper describes the sub-component analyses and tests, the design and analyses of the full-scale test articles, and includes results from the full-scale dynamic tests [6]. The results of the dynamic tests were compared to the design requirements and the pre-test finite element predictions. Both crashworthy component designs met the design requirements and the tests were successful in demonstrating the effectiveness of the two design concepts individually. Test results were consistent with finite element model predictions in terms of energy absorption capability, force-displacement behavior, and modes of deformation.

The overridden locomotive involved in the Red Oak accident was compliant with the latest regulations, specifically AAR S-580 [7]. When these regulations were adopted, PBCs and DACs were discussed, but the technology was not sufficiently mature. This research program endeavors to develop this technology further.

Industry has raised concerns that push-back couplers may trigger prematurely, and may require replacement due to unintentional activation as a result of service loads. Push-back couplers are designed with trigger loads greater than the expected maximum service loads experienced by conventional couplers. Analytical models are typically used to determine these required trigger loads. Researchers conducted two sets of coupling tests to demonstrate this, one with a conventional locomotive equipped with conventional draft gear and coupler and another with a conventional locomotive retrofit with a PBC. These tests will allow a performance comparison of a conventional locomotive with a CEM-equipped locomotive during coupling. In addition to the two sets of coupling tests, vehicle-to-vehicle compatibility tests of CEM-equipped locomotives as well as a train-to-train test are also planned. This arrangement of tests will allow for evaluation of the CEM-equipped locomotive performance and the comparison of measured with simulated locomotive performance in the vehicle-to-vehicle and train-to-train tests.

1.2 Objectives

The objectives of the locomotive crashworthiness research program are to demonstrate that the integrated locomotive crashworthy system, combining a PBC and DAC, performs as expected in service, provides crashworthiness compatibility with a range of equipment, and exhibits increased crashworthiness over conventional equipment. A series of full-scale dynamic tests have been planned to achieve these objectives. The first set of tests are coupling tests of a conventional F40 locomotive coupling with a Budd M1 cab car (M1). The second set of tests are coupling tests of an F40 retrofit with a PBC coupling with an M1. This arrangement of the tests will allow comparison of the conventional coupler performance with the performance of the PBC.

1.3 Overall Approach

Before demonstrating the robustness of the PBC, it was important to establish a baseline for conventional coupling to determine the maximum non-destructive conventional coupling speed. Therefore, conventional coupling tests were conducted first. These tests established a baseline for comparison with future CEM coupling tests. The objective of the tests was to measure and characterize the structural performance of the conventional coupler and the coupling vehicles under a range of increasing dynamic coupling speeds until damage occurs in the coupler system. The critical result was the maximum non-destructive conventional coupling speed.

Researchers conducted computer simulations of the impacts prior to the tests and served to inform the testing decisions made concerning the conventional coupling tests. The results of the conventional coupling tests were compared to the analytical predictions and evaluations made on the performance of the equipment.

After the conventional coupling tests, TTCI retrofit a PBC onto an F40 locomotive and a series of dynamic CEM coupling tests were conducted. The primary objective was to demonstrate the robustness of the PBC design and determine the impact speed at which PBC triggering occurs. The test objective was to measure and characterize the structural performance of the PBC and the coupling vehicles under a range of increasing dynamic coupling speeds until damage occurred in the coupler system.

The results from the conventional coupling tests, as well as computer simulations, informed the testing decisions made concerning the CEM coupling tests. The results of the CEM coupling tests were then compared to the analytical predictions and evaluations made on the performance of the equipment.

1.4 Scope

This report details the conventional coupling tests and the CEM coupling tests. This includes the test set-up, the test results, and an analysis of the results. A comparison of the conventional coupling tests and the CEM coupling tests are provided, as well as conclusions and next steps in the program.

1.5 Organization of the Report

This report comprises the following sections:

Section 2 discusses the conventional coupling tests in detail including the test scenario, the test results and a comparison with the pre-test analyses.

Section 3 provides the same information for the CEM coupling tests and analysis of data obtained from the strain gages installed on the equipment.

Section 4 develops comparisons between the conventional and CEM coupling tests and describes relevant observations, assessments of vehicle damage and a comparison of significant measurement results obtained.

Section 5 contains a brief summary of the report, conclusions drawn from the tests and plans for the next steps in the program.

2. Conventional Coupling Test

The conventional coupling tests were conducted at the Transportation Technology Center (TTC) in Pueblo, Colorado. For these tests, the locomotive impacted the stationary M1 car at increasing speeds until damage occurred. The coupling tests were conducted repeatedly with the same conventional F40 locomotive and M1 passenger car, starting at 2 mph for the first test, and increasing in increments of 2 mph until damage occurred in either vehicle. For these impact tests, the M1 car was braked.

The objective of this effort was to determine the maximum non-destructive conventional coupling speed by conducting conventional coupling tests. This established a baseline for comparison with the CEM coupling tests. The structural performance of the conventional coupler and the coupling vehicles was measured and characterized under a range of dynamic coupling speeds.

The information researchers sought from the conventional coupling tests included the longitudinal, vertical and lateral accelerations of the equipment and the displacements of the couplers. They also sought information on the sequence of events, e.g., the timing of the coupling and then the bottoming of the draft gear (when the coupler had exhausted its draft stroke). The equipment and components were visually inspected externally after each coupling test to ascertain the condition of the equipment and determine if any damage had occurred. However, due to the nature of couplers, draft gears, and draft pockets, it was difficult to inspect internal areas, such as the draft gear pocket and draft gear components, for damage. Additionally, conducting a complete a teardown of the draft gear systems of both the locomotive and cab car after each impact test was not practical. A post-test inspection of the equipment was conducted and is described in the results section.

The force-crush characteristic (i.e., the load that the couplers and supporting structure develop during the coupling procedure with respect to the relative crush/displacement of the vehicles) is a key characteristic of the couplers and the cars. One purpose of these tests was to take measurements for comparison with analytical predictions to validate that such predictions were accurate. Another comparison included measurements taken from the CEM coupling tests that were conducted after these tests.

2.1 Test Scenario: Coupling Impact

Coupling tests were conducted repeatedly with the same conventional F40 locomotive and M1 cab car, starting at 2 mph for the first test, and increasing in increments of 2 mph, as shown schematically in Figure 2. At impact, the F40 locomotive was traveling at speed and the M1 cab car was braked. The couplers on both vehicles were open upon impact and were expected to couple with each other. The vehicle weights were approximately 246 kips for the locomotive and 73 kips for the M1 car.

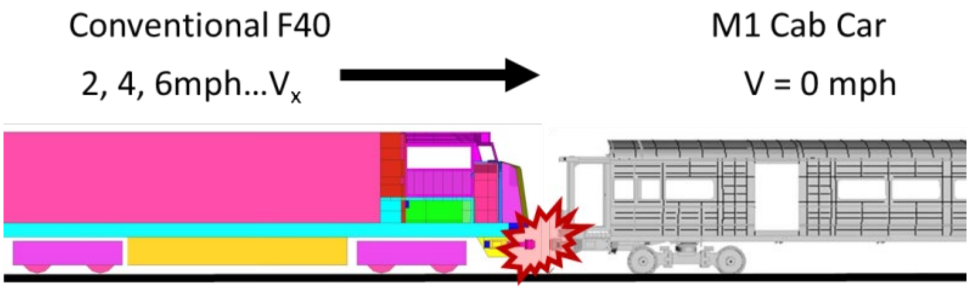

Figure 2. Schematic of conventional coupling test initial conditions

2.1.1 Equipment

The equipment used for the conventional coupling test included a conventional F40 locomotive and an M1 passenger cab car. F40 Locomotive 202 was used in the tests and can be seen in Figure 3.

Figure 3. F40 Locomotive 202 used in the conventional coupling tests

Figure 4 shows the F40 draft gear and yoke. The draft gear provides cushioning for longitudinal train loads and for coupling. The draft gear is double acting, in the sense that a single pack of rubber/metal plates provides cushioning in both buff and draft. These are key elements that were evaluated in the coupling tests. The load imparted to the locomotive is a function of the draft gear stiffness, as well as the stiffness of the structure that supports the draft gear. All of these components were highly loaded during the tests.

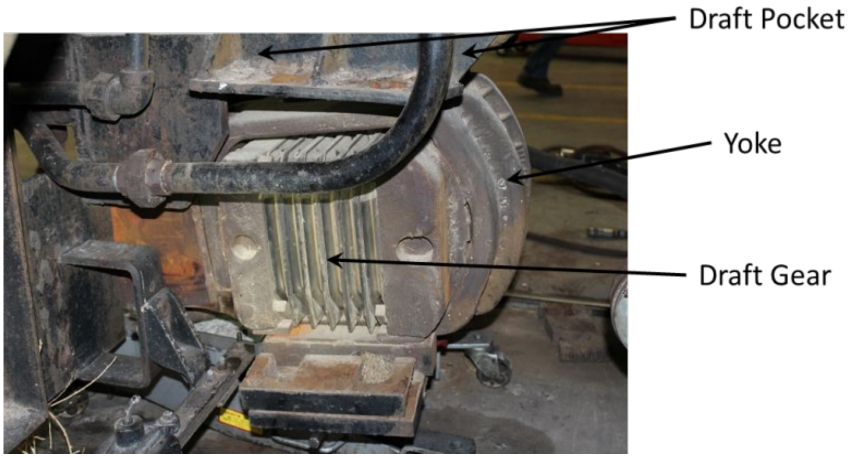

Figure 4. F40 locomotive draft gear and yoke

A photograph of the M1 cab car used in the conventional coupling tests is shown in Figure 5. As can be seen in the photograph, this M1 cab car (9324) exhibits damage from a small fire. However, the structural elements of the end frame are unharmed and intact and the rest of the vehicle is undamaged.

Figure 5. M1 cab car 9324 with some fire damage

Figure 5 shows the M1 draft gear and yoke. The draft gear is single-acting, so there are two sets of rubber/metal plates. One pack acts in buff and the other acts in draft. These are key elements that were evaluated in the coupling tests. The load imparted to the cab car underframe is a function of the draft gear stiffness, as well as the stiffness of the structure that supports the draft gear. Like the locomotive's components, these cab car components were highly loaded during the test.

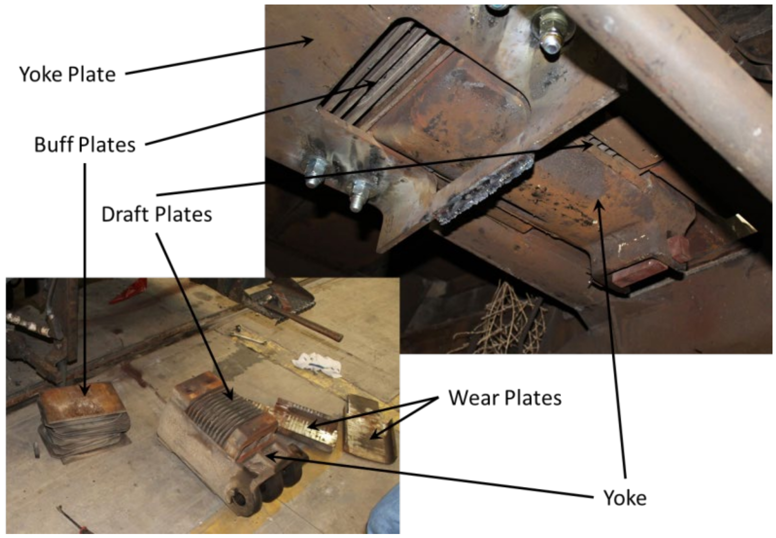

Figure 6. M1 draft gear and yoke

2.1.2 Instrumentation

Measurements were made with accelerometers, displacement transducers, and high-speed video cameras. These instruments captured the gross motions of the equipment, the relative motion of the couplers and draft gear, and the sequence of events, e.g., coupling, stroking of the draft gears, and eventual damage. The coupling speed of the locomotive was measured with radar and a reflector-based sensor.

Figure 7 shows a schematic illustration of the accelerometer locations on the M1 car. Accelerometers were placed in similar locations on the F40 locomotive. The accelerometers on the carbody captured the three-dimensional gross motions of the carbody—longitudinal, lateral, and vertical accelerations, as well as yaw, pitch, and roll. There were 17 accelerometer channels and 8 displacement transducer channels utilized for each vehicle, resulting in 50 total data channels.

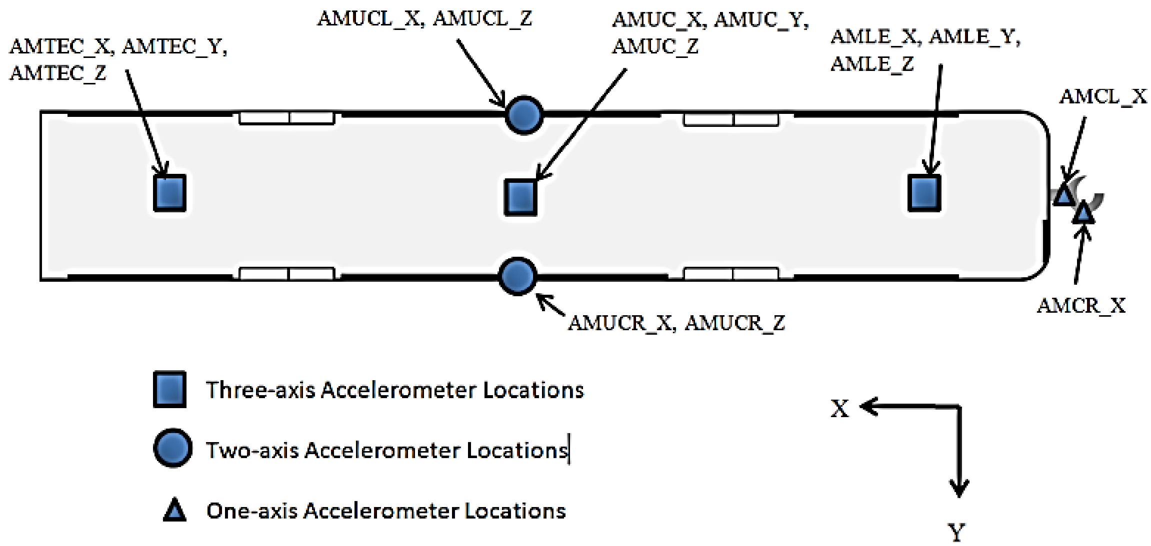

Figure 7. Schematic illustration of M1 cab car accelerometer locations

Displacement transducers were placed on the locomotive and the M1 couplers. Relative vertical, lateral, and longitudinal displacements were measured. These measurements captured the longitudinal response of the draft gear, and any motions that may have led to lateral buckling or override. Displacement transducers were also placed on both vehicle underframes to measure potential center sill or draft gear box deformation. In addition to the coupler and underframe transducers, the vertical displacements of the secondary suspension were also measured. The intent was to capture any pitching motion of the vehicles.

Redundant speed sensors measured the impact speed of the locomotive when it was within 20 inches of the impact point. The speed trap was a reflector-based sensor. It used ground-based reflectors separated by a known distance and a vehicle-based light sensor that triggered as the locomotive passed over the reflectors. The last reflector was within 10 inches of the impact point. The time interval between passing the reflectors was recorded. Speed was then calculated from distance and time. Backup speed measurements were made with a handheld radar gun.

Six high frame rate and four conventional frame rate high-definition (HD) video cameras documented each impact. The tests were conducted on tangent track with an approximate 0.85 percent grade. The locomotive was rolled back from the M1 cab car and released from the appropriate location to develop the intended impact speed. Speed trials were conducted prior to the test date to determine the distance needed to roll back the locomotive for each desired impact speed. Shortly before each test the release distance was adjusted based on wind speed and direction.

2.2 Test Results

A total of six impact tests were conducted, with the final test conducted at a target speed of 12 mph. Table 1 shows the actual speeds achieved for each impact test. All actual speeds were within ±0.3 mph of the corresponding target speed. In all but the last two tests (10 mph and 12 mph), the vehicles coupled together at impact. The vehicles remained on the tracks for all of the coupling tests. After each coupling test, a visual inspection of both vehicles was conducted by Volpe and TTCI personnel to identify any structural damage resulting from the impact.

Table 1. Conventional coupling tests: Target speeds vs. test speeds

Test	Target Speed (mph)	Actual Speed (mph)
1	2	1.9
2	4	3.9
3	6	5.7
4	8	7.9
5	10	10.0
6	12	11.9

2.2.1 Tests 1 and 2: 2 mph and 4 mph

The actual speeds of the impact tests were 1.9 mph and 3.9 mph. The vehicles coupled upon impact in both tests. Upon visual inspection, there was no apparent structural damage to either the F40 or the M1 as a result of either impact.

2.2.2 Test 3: 6 mph

The actual speed of the impact test was 5.7 mph. The vehicles coupled upon impact. Upon visual inspection, there was no apparent structural damage to the F40. Similarly, there was no apparent structural damage to the coupler, draft gear or draft pocket of the M1. However, there was some very minor dimpling of the M1 car shell at the front-left side sill connection to the truck, as indicated by the red circles of Figure 8.

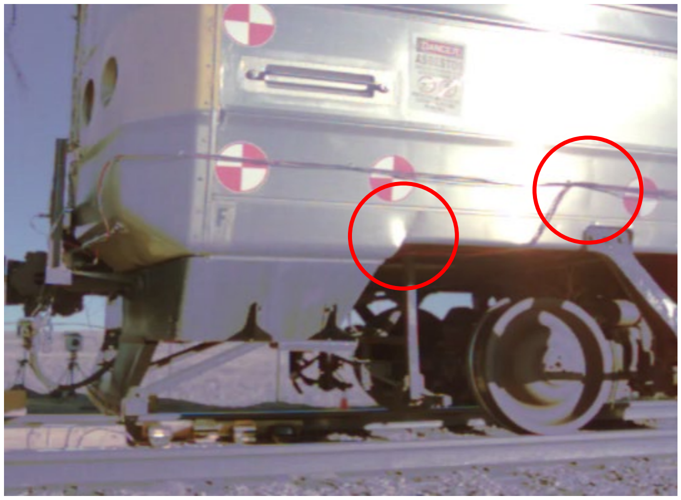

Figure 8. Dimpling of M1 shell at front-left side sill truck connection after 5.7 mph impact test

2.2.3 Test 4: 8 mph

The actual speed of the impact test was 7.9 mph. The vehicles coupled upon impact. After this impact test, a borescope was employed on the M1 car to try to determine if there was damage to the draft gears and inside the draft gear pockets. However, the quality of the borescope images proved unhelpful in this endeavor.

Upon visual inspection, there was no apparent structural damage to the F40. Similarly, there was no apparent structural damage to the coupler, draft gear or draft pocket of the M1. The dimpling of the M1 car shell at the front left side sill connection to the truck became more pronounced, as indicated by the red circles in Figure 9.

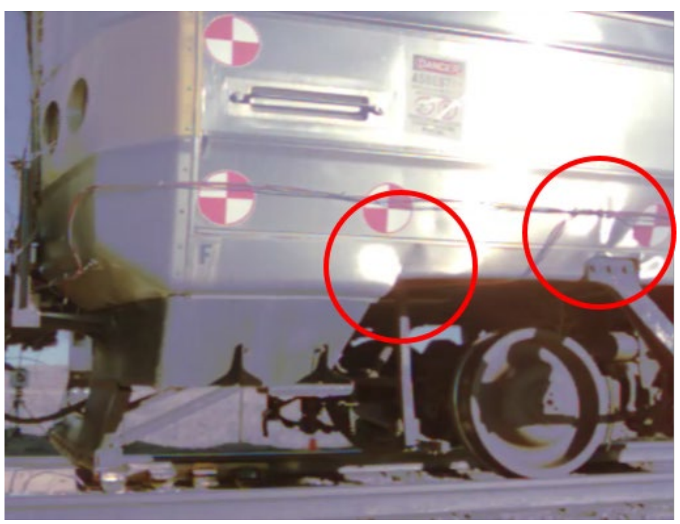

Figure 9. More pronounced dimpling of M1 shell at front-left side sill truck connection after 7.9 mph impact test

2.2.4 Test 5: 10 mph

The actual speed of the impact test was 10.0 mph. During this test, both the locomotive coupler locking pin and the M1 coupler hinge pin lifted due to vertical oscillations of both couplers as a result of the impact. This prevented the vehicles from coupling. The M1 coupler hinge pin can be seen in Figure 10. Upon visual inspection, there was only very minor damage to the F40 locomotive. A small chip was broken out of the locomotive coupler knuckle, as indicated in Figure 10.

Figure 10. M1 coupler (left) hinge pin and locomotive coupler (right) knuckle damage

In the M1 car, there was a bulge in the left draft sill at the bellmouth due to the coupler shank pushing on the coupler stops inside the bellmouth. This bulge can be seen inside the red circle in Figure 11. The coupler stops pushed in and were deformed by the coupler shank, as shown in Figure 12. The left coupler stop (located on the right side in the photo) was pushed in further and was more deformed than the right coupler stop.

Figure 11. Bulging of M1 left draft sill due to coupler shank pushing on coupler stops inside bellmouth

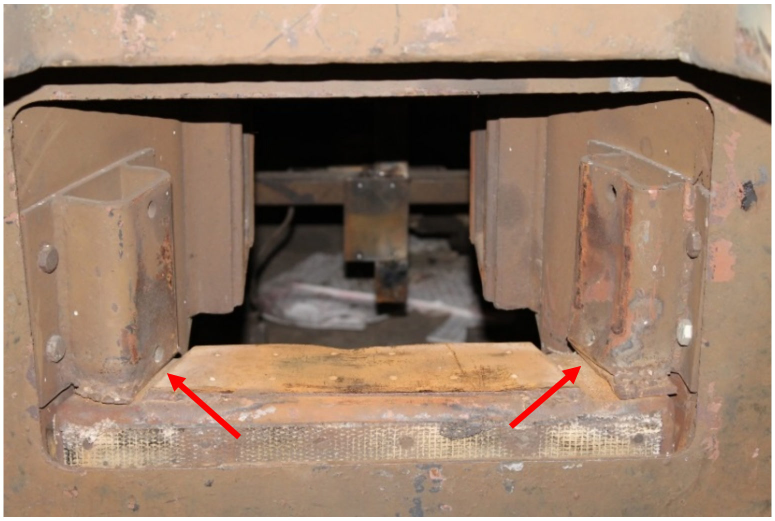

Figure 12. M1 coupler stops deformed by coupler shank

On the M1 car, the impact force developed in the 10 mph impact caused the exterior right flange of the draft pocket to deform, as indicated in Figure 13. The force of the impact through the draft gear also caused one of the buff plates in the draft gear to bend, as indicated in Figure 14.

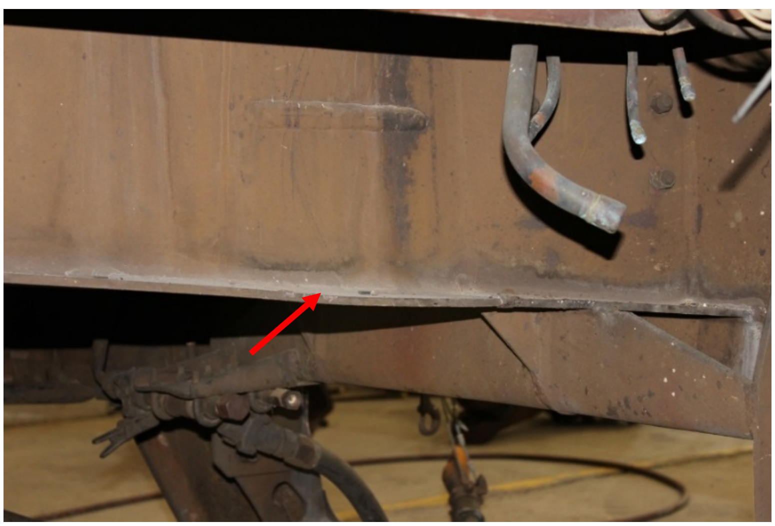

Figure 13. Deformed exterior right flange of M1 draft pocket

Figure 14. M1 bent buff plate in draft gear

On the M1 car, this impact caused the side sill to buckle at the front-left truck connection. Figure 15 shows an exterior view of the buckle of the side sill, and Figure 16 shows an interior view of the buckled side sill at the front-left truck connection. There was also some minor dimpling of the M1 shell at the side sill on the right side at the front truck connection, but the damage was more extensive on the left side.

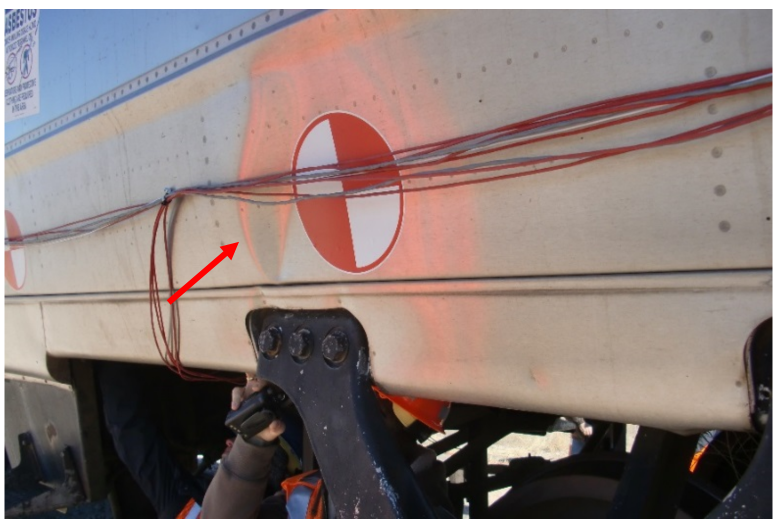

Figure 15. M1 side sill buckled at front-left truck connection (exterior view)

Figure 16. M1 side sill buckled at front-left truck connection (interior view)

2.2.5 Test 6: 12 mph

The actual speed of the impact test was 11.9 mph. As in the 10 mph test, the vehicles did not couple during this test, and the M1 coupler hinge pin again lifted during impact. Upon visual inspection, there was no apparent additional damage to the F40 locomotive.

In the M1 car, the 12 mph impact caused damage at the side sill front left truck connection, as shown in Figure 17. The impact also caused an underframe member to deform near the front-left truck, as shown in Figure 18, and the front belt loop of the front truck to be severed, as shown in Figure 19.

Figure 17. M1 side sill front-left truck connection damage

Figure 18. M1 underframe member bent near front truck connection, left side

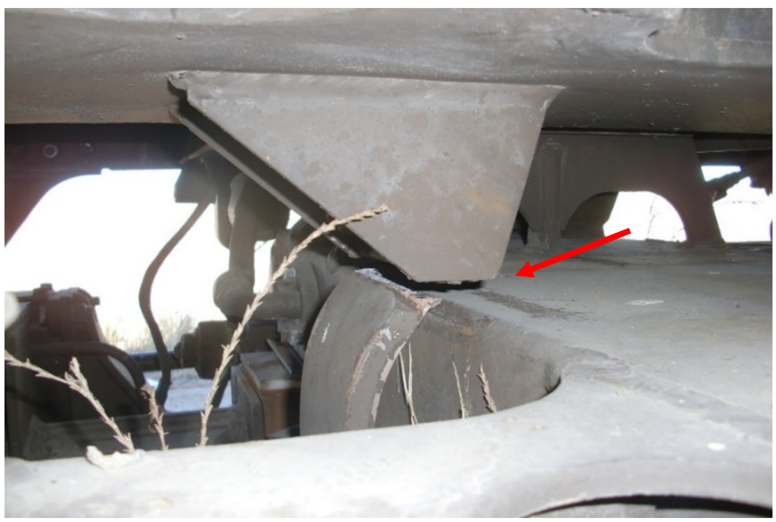

Figure 19. M1 front belt loop of front truck severed

The 12 mph impact worsened the buckle at the side sill at the front-left truck connection, as shown in the exterior view of Figure 20 and the interior view of Figure 21, effectively crippling the M1 car. The red arrows in Figure 21 indicate cracks in the side sill. The minor dimpling that occurred in the 10 mph impact on the front-right shell at the side sill connection to the front-right truck worsened due to buckling of the side sill at this location in the 12 mph impact. This can be seen in the exterior view of Figure 22 and the interior view of Figure 23. The red arrows in Figure 23 indicate cracks in the side sill. Testing was halted after this test, as there was extensive damage to the M1 cab car.

Figure 20. M1 side sill front-left truck connection (exterior view)

Figure 21. M1 side sill front-left truck connection (interior view)

Figure 22. M1 side sill front-right truck connection (exterior view)

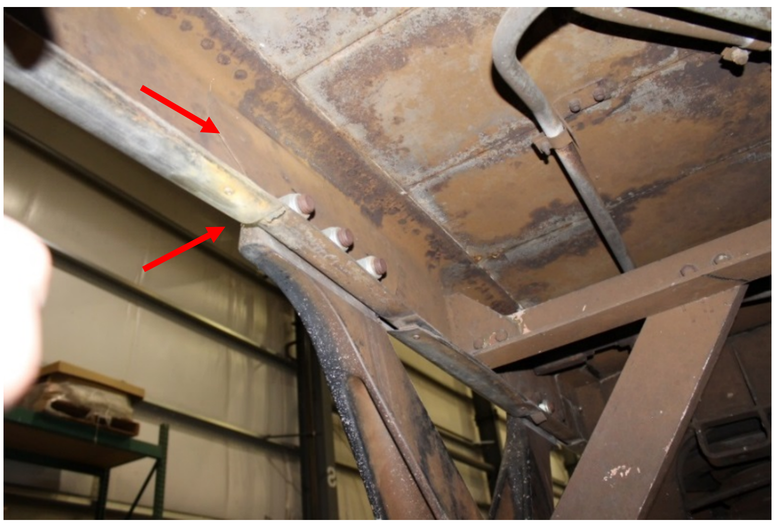

Figure 23. M1 side sill front-right truck connection (interior view)

2.2.6 Damage to Draft Systems

After the tests were conducted, a post-test teardown of the vehicle draft gear systems was performed to determine the internal damage sustained as a result of the six impact tests. A thorough inspection of the F40 locomotive draft gear and draft pocket showed no apparent structural damage to the draft gear system and draft pocket.

The post-test inspection of the M1 cab car draft gear and draft pocket revealed that the longitudinal members on both sides of the draft pocket were deformed, as shown in Figure 24 and Figure 25. Two of the buff plates of the M1 draft gear were also bent as a result of the six impact tests, as shown in Figure 26.

Figure 24. M1 interior draft pocket bent longitudinal member, right side

Figure 25. M1 interior draft pocket bent longitudinal member, left side

Figure 26. M1 bent buff plates

2.2.7 Test Data

The test data were filtered using a channel frequency class (CFC) 60 filter consistent with the requirements of SAE J211 [8]. The raw data from the test can be found in an FRA report [9]. Forces were obtained from the accelerometer data by multiplying the mass of the vehicle by the acceleration measured at each accelerometer location. The initial impact energy was calculated using the actual impact speed and the mass of the locomotive. The impact forces and impact energies associated with each test are summarized in Table 2. The locomotive carbody accelerometer data were used in these calculations.

Table 2. Conventional coupling tests: Impact forces and energies

Test	Impact Speed (mph)	Impact Force (kips)	Impact Energy (ft-kips)
1	1.9	137	29
2	3.9	258	123
3	5.7	508	265
4	7.9	963	513
5	10.0	1321	817
6	11.9	1732	1160

The coupling force as a function of the impact speed is plotted in Figure 27. The plot is annotated to show the progression of damage to the M1 cab car. Again, very little damage was incurred by the locomotive through all six impact tests. As shown in the figure, no damage to the M1 occurred in the first two impact tests (1.9 mph and 3.9 mph). Dimpling of the M1 shell at the location where the side sill meets the front truck attachment occurred as a result of the 5.7 mph impact. This dimpling became more pronounced as a result of the 7.9 mph impact. The 10.0 mph impact resulted in more damage to the side sill at the front truck connection, as well as damage to the bellmouth and underframe. The 11.9 mph impact resulted in effectively crippling the side sill of the M1 cab car.

The main objective of this effort was to determine the maximum non-destructive conventional coupling speed. Figure 27 shows the measured coupling force as a function of impact speed. At 2 mph and 4 mph, no visible damage occurred to either vehicle. Between 4 mph and 6 mph, damage began to occur. At speeds greater than 6 mph, there was visible damage. Therefore, coupling speeds should be kept under 6 mph to prevent damage. This is consistent with the Association of American Railroads' General Code of Operating Rules [10], which specifies that couplings occur "at a speed of not more than 4 mph."

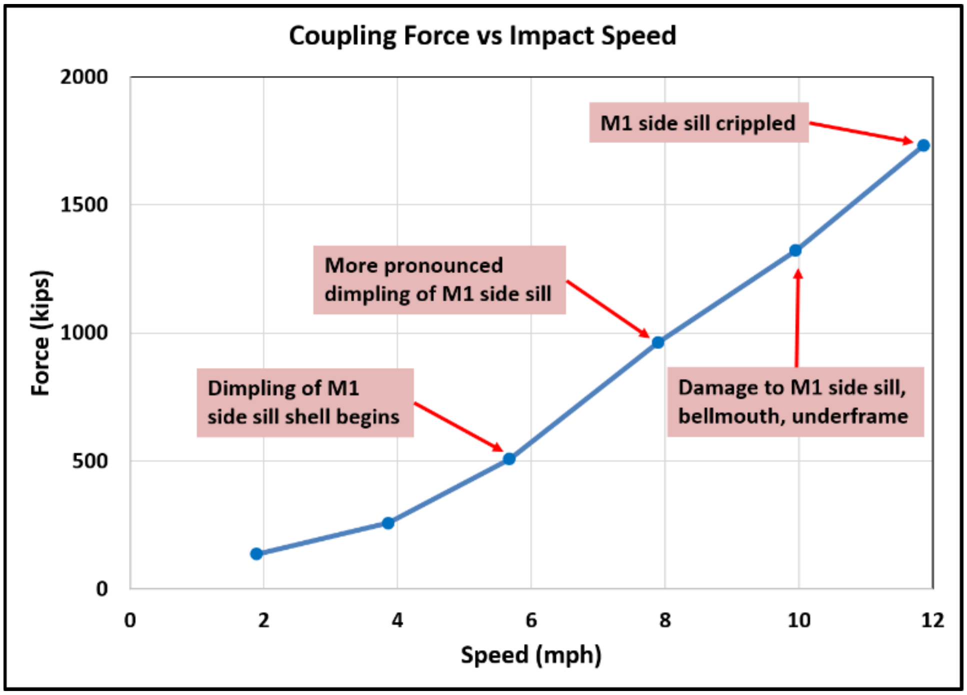

Figure 27. Coupling force as a function of impact speed

2.3 Comparison to Pre-Test Analysis

A simplified, one-dimensional, two-degree of freedom, dynamic lumped-parameter model of the coupling test was developed prior to the tests, shown schematically in Figure 28. The M1 cab car was represented by a single mass, and the F40 locomotive was also represented by a single mass. The draft gears acted as a spring between the two masses. The model included the longitudinal braking force acting on the M1. The primary purpose of the model was to estimate the peak force acting between the vehicles as a function of coupling speed.

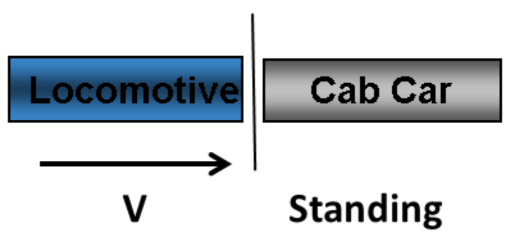

Figure 28**. Schematic of one-dimensional two-degree-of-freedom lumped parameter coupling model**

Figure 29 shows the force-displacement characteristics input into the simplified model. The characteristic was that of a relatively soft spring with a relatively hard stop. In such cases, the peak force was sensitive to the stiffness of the stop. Accordingly, a range of bottoming stiffnesses was analyzed: stiff, nominal, and soft. The bottoming stiffness was a function of both the draft gear itself and the support provided to the draft gear by the locomotive and cab car underframes.

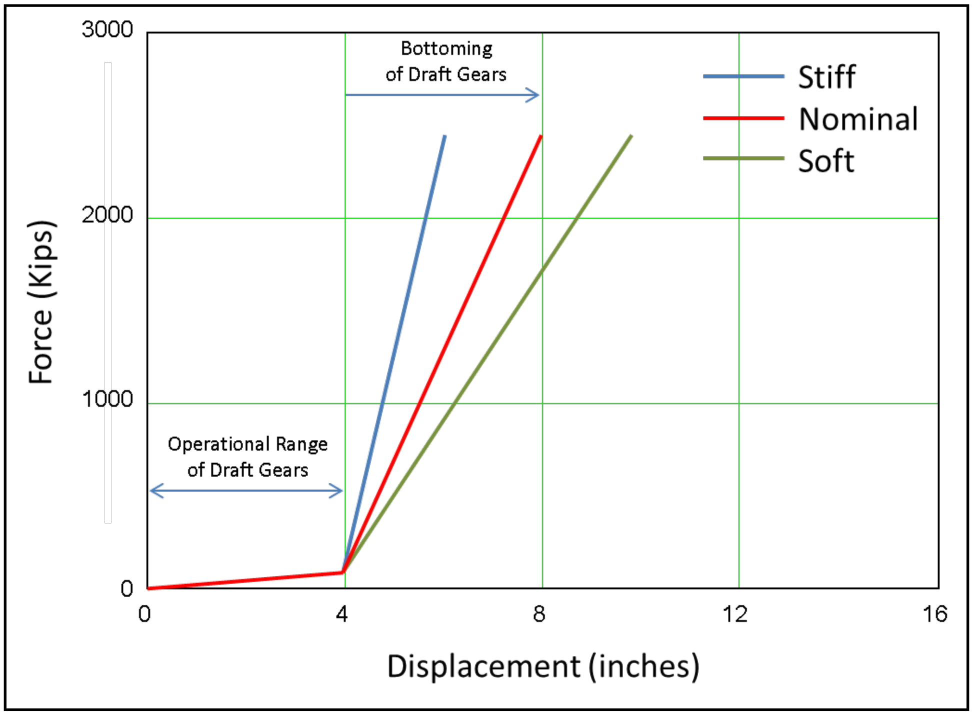

Figure 29. Input force-displacement characteristics for lumped-parameter model

Figure 30 shows peak coupling force as a function of coupling speed for the three bottoming stiffnesses: stiff, nominal, and soft. The graph is also annotated with the M1 car elastic strength, static crippling strength, and dynamic crippling strength [11]. Prior to the test, the coupler load was predicted to exceed the M1 carbody's static elastic strength for coupling speeds between 4 and 7 mph. The coupler load was predicted to exceed the M1 cab carbody's static crippling strength for coupling speeds between 6 and 10 mph. Researchers predicted that damage would occur for coupling speeds between 6 and 8 mph. This compared favorably with the test result that coupling speeds should be kept under 6 mph to prevent equipment damage.

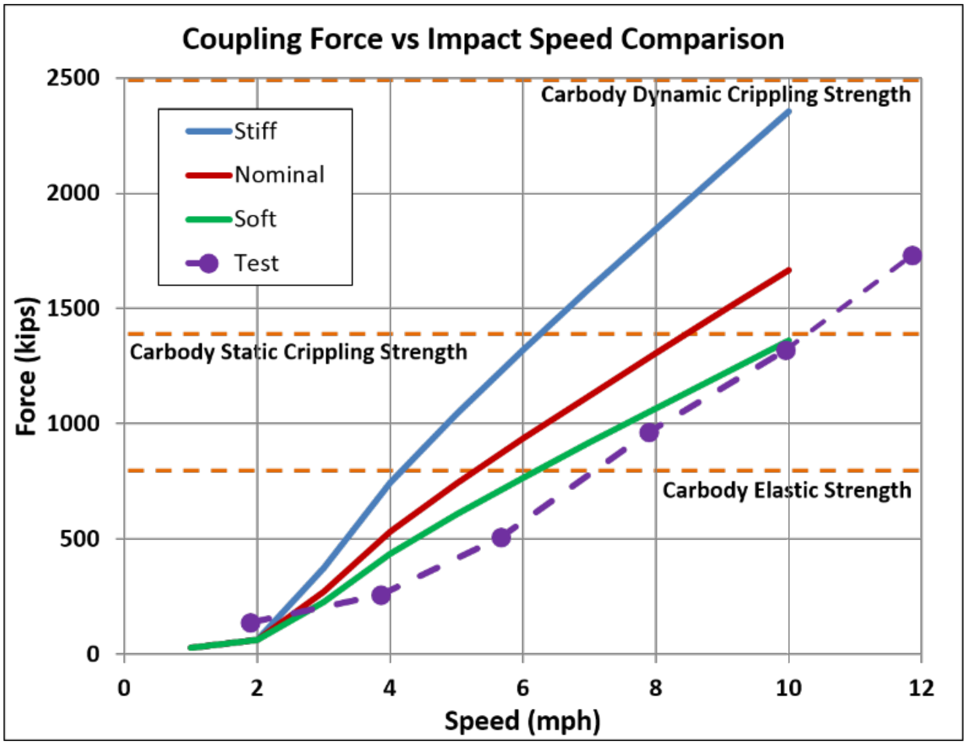

Figure 30. Peak coupling force as a function of coupling speed compared to results from lumped-parameter model

Note that the three M1 carbody strengths and the three predictions shown in Figure 30 were based on the assumption that the load path passed through the carbody alone. However, the dimpling and subsequent crippling of the M1 side sills that resulted from the impact tests indicated that a substantial portion of the load was borne by the truck attachments. This behavior could not have been captured by the simplified, one-dimensional model, since the entire M1 cab car was represented by a single mass.

The forces measured in the impact tests are also plotted with the model predictions and M1 carbody strengths in Figure 30. Despite the difference in load path, the figure shows that the results of these conventional coupling tests compared favorably with pre-test predictions of the simplified model utilizing the soft stiffness assumption.

3. CEM Coupling Test

The CEM coupling tests were also conducted at the TTC. In preparation, the two CEM components, a DAC, and a PBC, were retrofit onto an F40 locomotive. The CEM coupling tests were conducted repeatedly with the same CEM-retrofit F40 locomotive and M1 cab car, with targeted impact velocities of 2 mph, 4 mph, 6 mph, 7 mph, 8 mph, and 9 mph, or until the PBC triggered. A total of six impact tests were conducted, with the final test conducted at a target speed of 9 mph. The vehicle weights were approximately 233 kips for the locomotive, and 90 kips for the M1 car.

The objective of the tests was to demonstrate the robustness of the PBC design and determine the impact speed at which PBC triggering occurred. The structural performance of the PBC and the coupling vehicles were measured and characterized under a range of dynamic coupling speeds until PBC triggering occurred. Measurements were taken to determine the force-crush characteristic (i.e., the load that the couplers and supporting structure develop during the coupling procedure), a key characteristic of the couplers and the cars.

The information measured from the CEM coupling tests included the longitudinal, vertical, and lateral accelerations of the equipment and the displacements of the couplers. The equipment and components were visually inspected externally after each coupling test to ascertain the condition of the equipment and determine if any damage had occurred. However, due to the nature of couplers, draft gears, and draft pockets, it was difficult to inspect internal areas, such as the draft gear pocket and draft gear components, for damage. Additionally, conducting a complete a teardown of the draft gear systems of both the locomotive and cab car after each impact test was not practical. A post-test inspection of the equipment was conducted and is described in the results section.

The force-crush characteristic (i.e., the load that the couplers and supporting structure develop during the coupling procedure) is a key characteristic of the couplers and the cars. One purpose of these tests was to take measurements for comparison with analytical predictions to validate that such predictions were accurate. Another comparison made was with the measurements taken from the conventional coupling tests.

3.1 Test Scenario: Coupling Impact

CEM coupling tests were conducted repeatedly with the same CEM-retrofit F40 locomotive and M1 cab car, with targeted impact velocities of 2 mph, 4 mph, 6 mph, 7 mph, 8 mph, and 9 mph, or until the PBC triggered, as shown schematically in Figure 31. At impact, the CEM F40 locomotive was traveling at speed and the M1 cab car was braked. The couplers on both vehicles were open upon impact and expected to couple with each other. The vehicle weights were approximately 246 kips for the locomotive, and 73 kips for the M1 car.

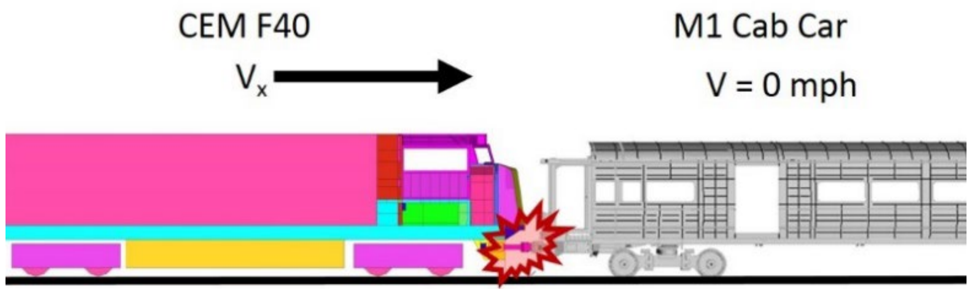

Figure 31. Schematic of CEM coupling test initial conditions

3.1.1 Equipment

The equipment used in the CEM coupling tests were retrofit F40 Locomotive 234, and M1 passenger cab car 8221, shown in the pre-test photograph of Figure 32. Figure 33 shows the DAC and PBC retrofit to the F40. Details of the fabrication and retrofit can be found in the References section [12]. These two components comprised the CEM system. Figure 34 shows the PBC installed within the sliding lug, and Figure 35 is an exterior view of the shear bolts, which hold the sliding lug to the draft pocket. During an impact that occurs at greater than typical coupling speeds, the PBC will trigger at approximately 680 kips. Once it is triggered, the PBC absorbs energy as it pushes back at that load level. When the PBC stroke is exhausted, the shear bolts are broken by the mounting impact force at approximately 1,000 kips. This causes the sliding lug to move back. At this point, the load path transfers from the PBC completely to the DAC, which crushes in a controlled manner, thereby absorbing more collision energy. The entire CEM system is designed to permit the colliding vehicle ends to engage while absorbing the energy of the collision. This minimizes lateral buckling and ramp formation due to uncontrolled crush, both of which promote override. The design development and requirements of the CEM components are detailed in previous papers [4], [5], [6].

Figure 32. Pre-test photo of M1 cab car 8221 (left) and F40 Locomotive 234 (right) used in the CEM coupling tests

Figure 33. The DAC (top) and the PBC (bottom) comprise the locomotive CEM system

Figure 34. PBC installed within the sliding lug

Figure 35. Exterior view of the shear bolts installed through the draft pocket

3.1.2 Instrumentation

Measurements were made with accelerometers, strain gages, displacement transducers, and high-speed video cameras. These instruments captured the gross motions of the equipment, the relative motion of the couplers and draft gear, the local deformations and load paths, and the sequence of events, e.g., coupling, stroking of the draft gears, and eventual damage. The coupling speed of the locomotive was measured with radar and a reflector-based sensor.

Figure 36 shows a schematic illustration of the accelerometer locations for the M1 car. Accelerometers were placed in similar locations on the F40 locomotive. The accelerometers on the carbody captured the 3-dimensional gross motions of the carbody—longitudinal, lateral, and vertical accelerations—as well as yaw, pitch, and roll.

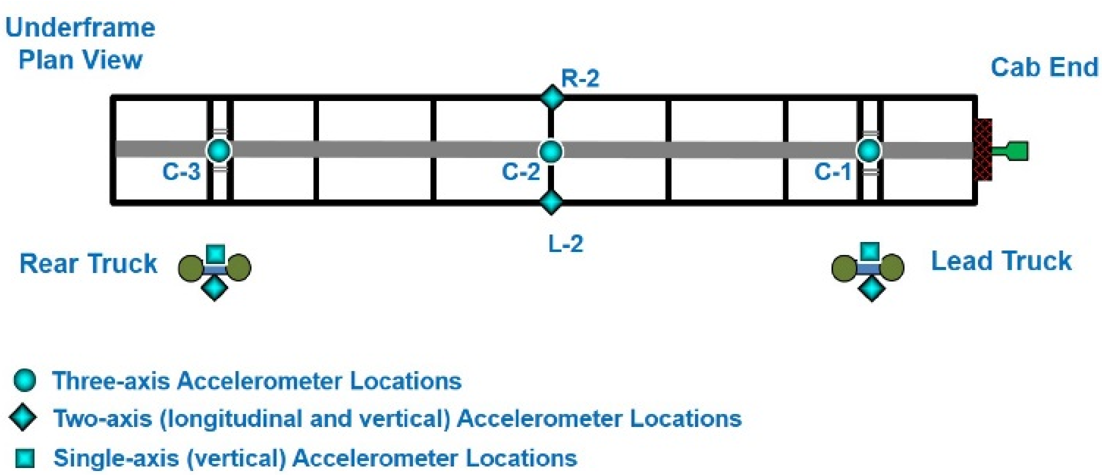

Figure 36. Schematic illustration of M1 cab car accelerometer locations

Displacement transducers and strain gages were employed to measure local structural deformations and load paths. Forty-three accelerometer channels, forty-nine strain gage channels, and fifteen displacement transducer channels were utilized for each vehicle, resulting in 107 total data channels for the tests.

Six high frame rate and four conventional frame rate high definition (HD) video cameras documented each impact. The tests were conducted on tangent track with approximately a 0.85 percent grade. The locomotive was rolled back from the M1 cab car and released from the appropriate location to develop the intended impact speed. Speed trials were conducted prior to the test date to determine the distance needed to roll back the locomotive for each desired impact speed. Shortly before each test the release distance was adjusted based on wind speed and direction.

3.2 Test Results

Table 3 shows the actual speeds achieved for each impact test. All actual speeds were within ±0.4 mph of the corresponding target speed. The tests were conducted with both couplers open, with the intention of coupling occurring. There was some initial misalignment of the couplers that was alleviated somewhat by the M1 coupler being shimmed for the tests. The shims did not completely correct the misalignment, but brought the couplers to within 2 inches of each other vertically. The vehicles remained on the tracks for all of the coupling tests.

Table 3. CEM coupling tests: Target speeds vs. test speeds

Test	Target Speed (mph)	Actual Speed (mph)	Vehicles Coupled?	PBC Triggered?
1	2	1.8	Yes	No
2	4	3.7	Yes	No
3	6	5.7	No	No
4	7	6.8	No	No
5	8	7.6	No	No
6	9	8.9	No	Yes

After each coupling test, a visual inspection of both vehicles was conducted by Volpe and TTCI personnel to identify any structural damage resulting from the impact. The vehicles coupled in the first two tests (2 mph and 4 mph), but not in the higher-speed impacts. The PBC triggered during the 9 mph test.

3.2.1 Tests 1 & 2: 2 mph and 4 mph

The actual speeds of the impact tests were 1.8 mph and 3.7 mph. The vehicles coupled upon impact in both tests. The PBC did not trigger. Upon visual inspection, there was no apparent structural damage to either the F40 locomotive or the M1 cab car as a result of either impact.

3.2.2 Test 3: 6 mph

The actual speed of the impact test was 5.7 mph. The PBC did not trigger. The vehicles did not couple upon impact, as seen in Figure 37. The figure also shows the small misalignment between the couplers. Upon visual inspection after the impact, there was no apparent structural damage to the F40. However, as a result of the impact, the front truck transom bar of the locomotive contacted the PBC flag (orange in color and shown in Figure 38) and bent its connection bolt. The purpose of the PBC flag is to give a more visible indication that the PBC deformation tube has triggered. When the PBC deformation is initiated, the flag's connection bolt is sheared, causing the flag to drop and hang by its chain.

There was no apparent structural damage to the coupler, draft gear, or draft pocket of the M1 cab car. However, the traction rod on the left side at the connection to the front truck was bent by the impact, as shown in Figure 39. This traction rod was replaced before the next test, the 7 mph impact.

Figure 37. Vehicles did not couple in the 6 mph impact

Figure 38. Front transom bar of locomotive hit PBC flag

Figure 39. M1 front-left traction rod deformed after 6 mph test

3.2.3 Test 4: 7 mph

The actual speed of the impact test was 6.8 mph. The vehicles did not couple upon impact. The PBC did not trigger. Upon visual inspection after the impact, there was no apparent structural damage to the F40. However, as a result of the impact, the front truck transom bar of the locomotive contacted the PBC again. Figure 40 shows the space between the rear of the draft pocket and the transom bar. The PBC flag could be seen at a slight angle, due to its interaction with the transom bar. The bolt connecting the flag was slightly bent, but still very much attached to the PBC.

Figure 40. PBC flag and transom bar after 7 mph impact

There was no apparent structural damage to the coupler, draft gear, or draft pocket of the M1 cab car. However, the new traction rod on the left side at the connection to the front truck was again bent by the impact, as shown in Figure 41. This traction rod was not replaced and was left as-is for the remaining tests, as there were no more replacements.

Figure 41. New M1 front left traction rod deformed again after 7mph test

3.2.4 Test 5: 8 mph

The actual speed of the impact test was 7.6 mph. The vehicles did not couple upon impact. The PBC did not trigger. Upon visual inspection after the impact, there was no apparent structural damage to the F40. However, again as a result of the impact, the front truck transom bar of the locomotive contacted the PBC. Figure 42 shows the space between the rear of the draft pocket and the transom bar. The PBC flag can again be seen at a slight angle, due to its interaction with the transom bar. The bolt connecting the flag was slightly bent, but still attached to the PBC, as shown in Figure 43.

Figure 42. PBC flag and transom bar after 8 mph impact

Figure 43. Close-up of the PBC flag and bolt after 8 mph impact

There was no apparent structural damage to the coupler, draft gear, or draft pocket of the M1 cab car. However, the deformed traction rod on the left side at the connection to the front truck was deformed further by the impact, as shown in Figure 44. As stated previously, this traction rod was not replaced and left as-is for the next test. New damage that occurred during this test was a broken piece of the front-left truck, as shown in Figure 45. This occurred due to interference between parts of the truck as a result of the deformed traction rod, as shown in the photograph on the right side of Figure 45.

Figure 44. M1 front-left traction rod deformed more after 8 mph test

Figure 45. Piece broken off of M1 front-left truck, with piece held up to its former place (left)

3.2.5 Test 6: 9 mph

The actual speed of the impact test was 8.9 mph. The vehicles did not couple upon impact. The PBC did trigger. Figure 46 shows the PBC flag detached from the PBC and hanging underneath the draft pocket. The flag was attached to the PBC by a bolt that sheared when the crush of the deformation tube was initiated. This allowed the flag to fall away from the PBC, indicating that tube crush has been initiated. Figure 47 shows the flag and its bolt, which was bent in the previous impacts due to interaction with the transom bar. However, this did not interfere with the operation and performance of the bolt, indicating the robustness in the design.

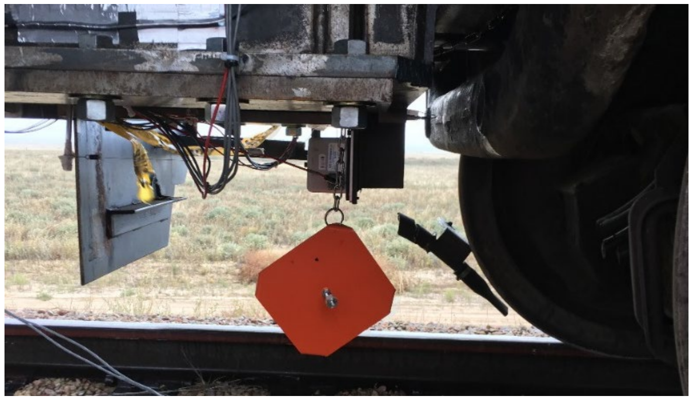

Figure 46. PBC flag detachment indicating the PBC was triggered

Figure 47. The PBC trigger indicator—an orange flag attached to the PBC by a bolt

The deformation tube was inspected after the tests to determine that approximately 5/8 inch of crush stroke was achieved. This can be seen by the peeling paint on the exterior of the tube in Figure 48 (right side) and Figure 49 (left side). The paint on the exterior of the tube is designed to peel off when deformation occurs. The other damage to the paint that is visible in the two photos occurred during shipment prior to the test. This had no effect on the performance of the deformation tube.

Figure 48. Cracked paint on the right side of the PBC deformation tube, indicating tube crush

Figure 49. Cracked paint on the left side of the PBC deformation tube, indicating tube crush

There was no apparent structural damage to the coupler, draft gear, or draft pocket of the M1 cab car. However, the deformed traction rod on the left side at the connection to the front truck was deformed even more by the impact, as shown in Figure 50. Note that there was no deformation to the side sills at the connections to the front truck. This was different from what occurred in the conventional coupling tests for the M1 car, where there was extensive deformation, and eventually fracture, in the side sills at the connections to the front truck. However, it is important to note that the maximum speed for the conventional coupling tests was 12 mph, compared to 9 mph for the CEM coupling tests.

Figure 50. M1 front left traction rod deformed more after 9 mph test

3.2.6 Post-Test Draft Pocket Damage Assessment

M1 Passenger Car

The draft gear of the M1 car was removed and inspected for damage several months after the tests were conducted. The draft pocket was inspected as well. There was no visible damage to either the draft gear components or the interior of the draft pocket.

CEM Locomotive

The PBC, sliding lug, and shear bolts of the CEM locomotive were removed and inspected for damage several months after the tests were conducted. The draft pocket was inspected as well. There was no visible damage to the PBC or the sliding lug.

There was minor damage found on the shear bolts and the draft pocket. Shear bolt 4 (left-rear middle position) experienced substantial galling between the bolt surface and the inner shear bushing. It was unclear if this damage was caused by the test or occurred when the bolt was removed.

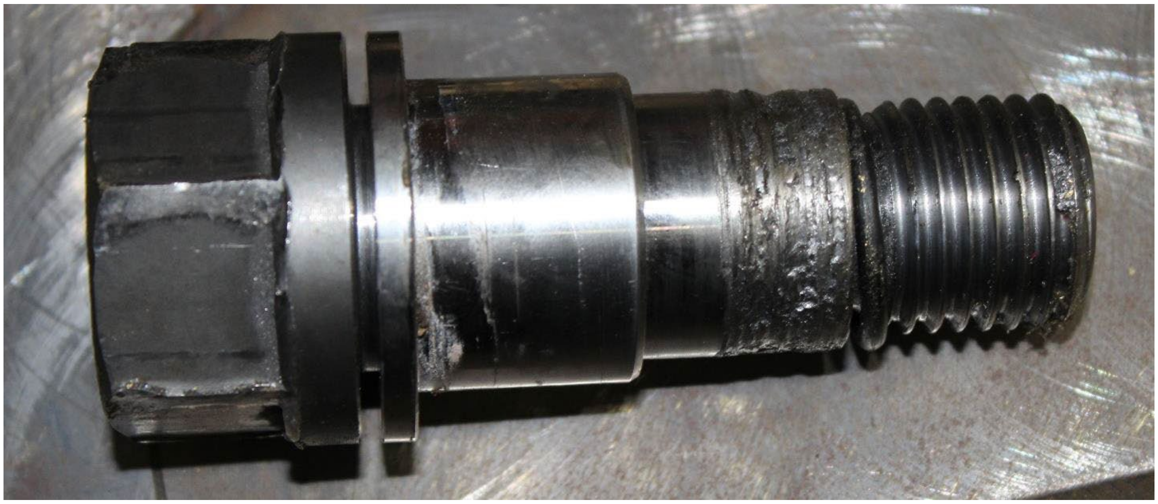

Figure 51**. Galling of shear bolt 4 (left rear middle position)**

The draft pocket bolt hole for shear bolt 4 also experienced surface damage. It was unclear if this was the result of the test, or occurred during the bolt's removal. It was unclear if any damage was done to the threads for this bolt in the sliding lug.

Figure 52**. Surface damage at bolt hole (shear bolt 4, left rear middle position)**

The coupler pocket hole for shear bolt 3 exhibited plastic deformation. This deformation appeared in the trailing end of the hole (toward the rear of the locomotive), on the inside face of the coupler pocket. The appearance of this deformation indicated a reasonable likelihood that it occurred during the test.

Figure 53. Plastic deformation of coupler pocket hole for shear bolt 3 (trailing end, toward rear of locomotive)

3.2.7 Test Data

The test data were filtered using a channel frequency class (CFC) 60 filter consistent with the requirements of SAE J211. The raw data from the test can be found in an FRA report [13]. Forces were obtained from the accelerometer data by multiplying the mass of the vehicle by the acceleration measured at the accelerometer location. The initial impact energy was calculated using the actual impact speed and the mass of the locomotive. The impact forces and impact energies associated with each test are summarized in Table 4. The locomotive carbody accelerometer data were used in these calculations.

Table 4. CEM coupling tests: Impact forces and energies

Test	Actual Speed (mph)	Impact Force (kips)	Impact Energy (ft-kips)
1	1.8	97	26
2	3.7	259	109
3	5.7	465	250
4	6.8	515	365
5	7.6	616	454
6	8.9	686	611

3.3 Comparison to Pre-Test Analysis

Prior to the test, a simplified lump-mass model was created to estimate the speed at which the PBC would trigger. This model estimated the PBC force-displacement behavior and utilized typical vehicle weights and the force-crush characteristic of a typical conventional locomotive draft gear. Figure 54 shows peak coupling force as a function of impact speed comparing the pre-test prediction with the test results. The figure shows that the test results compared favorably with the prediction.

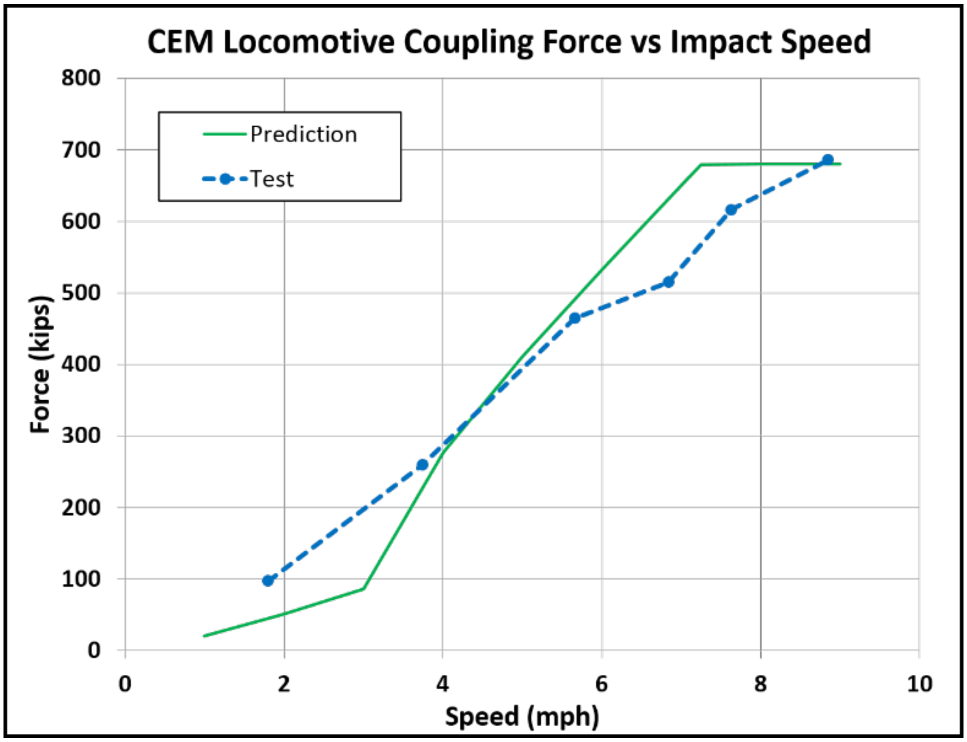

Figure 54. Peak coupling force as a function of impact speed

However, the model predicted that triggering of the PBC would occur at an impact speed between 7 mph and 8 mph. The test demonstrated that the PBC triggered at just under 9 mph. Additionally, the pre-test modeling predicted that damage would occur in the M1 truck-to-carbody connection at speeds above 5 mph. This occurred in the tests, as shown in Figure 39. The traction rod experienced bending in the 5.7 mph test as well as in each successive test at higher impact speeds.

As part of the collaboration to conduct the CEM coupling tests, Voith (the PBC supplier) provided updated dynamic measurements of the draft gear and PBC behavior. The plot in Figure 55 shows an idealized representation of the force-displacement behavior of the Voith PBC retrofitted onto the F40. This characteristic did not include the contribution of the DAC in the collision. The PBC draft gear characteristic had more than twice the energy absorbing capacity than a typical conventional draft gear.

TTCI measured the final weights of the equipment after the test was conducted. The retrofitted CEM locomotive weighed 232,600 lbs and the M1 cab car weighed 89,700 lbs. With the correct masses and the idealized PBC characteristic updated after the conduct of the test, a post-test collision dynamics model estimated that the PBC triggered between 8 and 9 mph. This estimate was closer to what occurred in the tests than the original pre-test prediction.

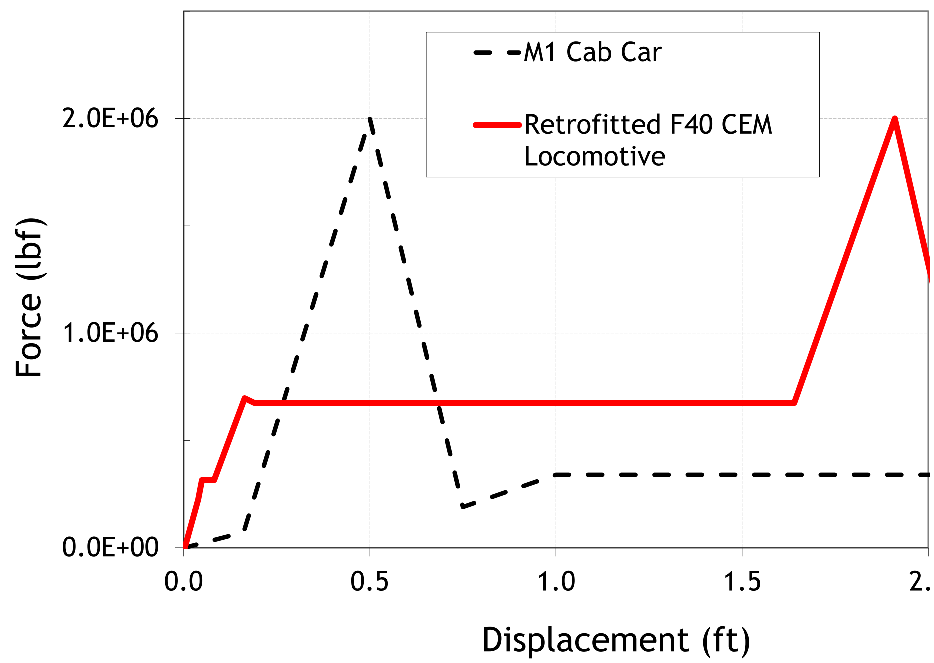

Figure 55. Idealized force-displacement characteristics of colliding vehicles

During the series of impact tests the colliding equipment coupled at speeds below 5 mph. The pre-test collision dynamics model assumed that the colliding equipment collided and remained engaged. At speeds above 5 mph, the colliding equipment did not couple. A post-test model is being developed to investigate the effect of this behavior on the model agreement with the test results.

3.4 Analysis of Strain Gage Data

Certain aspects of the strain gage data were analyzed. Strain gage locations can be found in another FRA report [13]. Representative measured strain-time histories are plotted in Figure 56. (Note that positive strains are compressive.) These are strain measurements for the five gages placed on the locomotive coupler. The plot at the left shows strain versus time results for the 4 mph test, and the plot at the right shows strain versus time for the 8 mph test. As is evident, the strains at 4 mph increased to compressive peaks ranging from 400 to 650 microstrain at about 0.18 second after impact, and then decreased in magnitude, changing sign at about 0.32 second, and increasing in magnitude to tensile peaks ranging from 100 to 300 microstrain at about 0.42 second. In contrast, the strains at 8 mph increased to compressive peaks ranging from 1000 to 1600 microstrain after about 0.12 seconds, and then drop to zero. It is likely that differences between the characteristics of the respective strain curves evident in Figure 56 were attributable to two key differences in the modes of deformation, as noted above:

- The vehicles coupled at 2 mph and 4 mph, but not at 6 mph or higher coupling speeds.

• The traction rod started to bend significantly at a coupling speed of 6 mph.

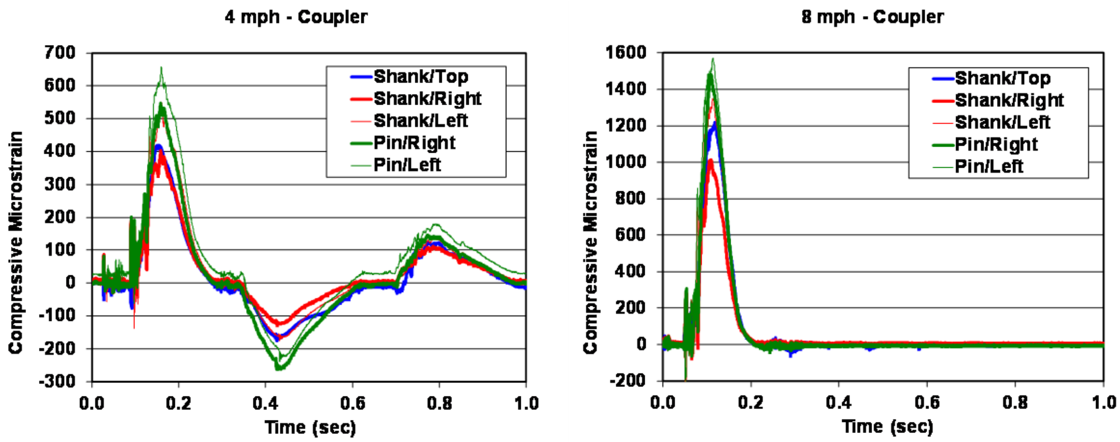

Figure 56. Strain-time histories for the five gages placed on the locomotive coupler: Left – 4 mph test; right – 8 mph hour test (positive strain is compressive)

The peak compressive strains at each of the five coupler locations are plotted as a function of impact speed shown at the left in Figure 57. As is evident, the peak strain magnitudes increased in an effectively linear fashion. Averages for the three shank locations and the two pin locations are shown at right in Figure 57. These results suggested that the strain in the shank region was about 30 percent higher than the strain in the pin region.

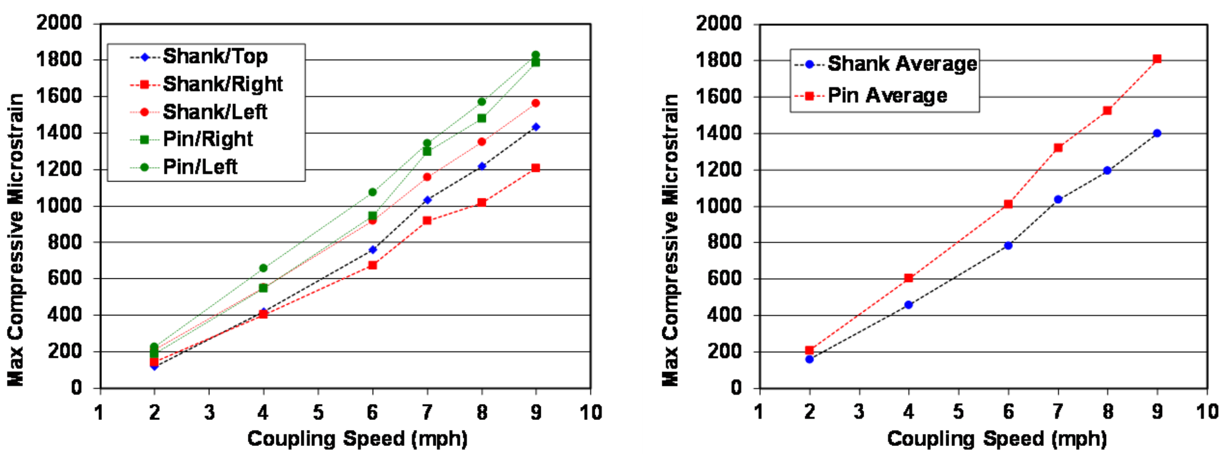

Figure 57. Left: Comparison of peak strains at each of the five gages placed on the locomotive coupler as a function of impact speed; right: Averaged values for shank and pin locations

Based on drawings and thickness data provided by Voith, the cross-sectional area, A, in the shank and pin regions of the coupler were estimated to be about 18.2 square inches and 14.0 square inches, respectively. Assuming the stress in the coupler is predominantly axial, an estimate of the force through these two sections can be made by multiplying the strain values by A × E, where E is Young's modulus, which is assumed to be 30 million psi. The resultant force through the shank and pin regions is plotted in Figure 58 as a function of coupling speed. For comparison, the estimate of force through the coupler that is derived from car body acceleration data (as calculated by TTCI) is also plotted. As is evident, the force through the two coupler locations were remarkably consistent with one another and indicated an effectively linear increase in coupler force with impact speed. For lower coupling speeds, these strain gage-based estimates of force were also consistent with acceleration-based estimates of force. For higher coupling speeds, the agreement was not as good, which may have been because the dynamics of the impact at these higher speeds did not lend themselves to estimates that assumed the entire mass of the vehicle was decelerating uniformly. The acceleration-based estimate of force at 7 mph seemed particularly low with respect to the other calculated values. During this test, the traction rod was deformed and was not replaced for the subsequent tests.

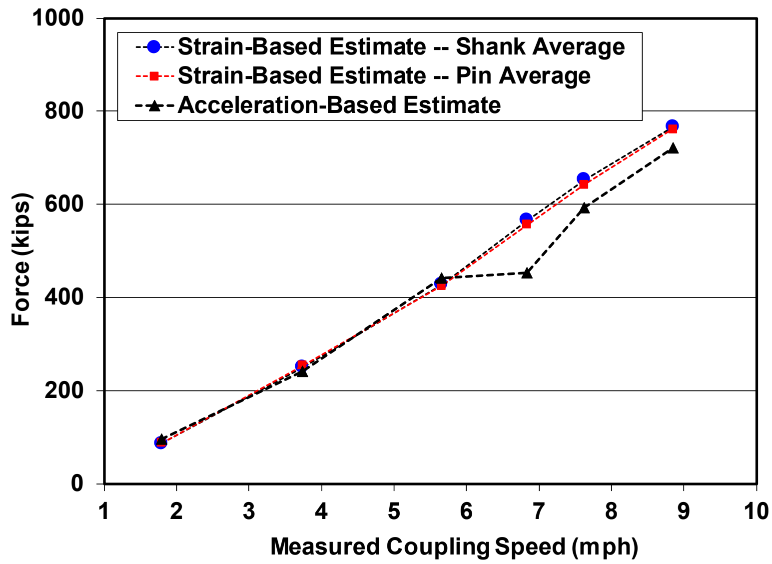

Figure 58. Comparison of strain-based estimates of force through coupler with acceleration-based estimate

Peak strain measurements at other gage locations on the locomotive are summarized in Figure 59 through Figure 61. Not surprisingly, the strain in the draft gear side plate, just behind the eight top and bottom bolt hole locations (Figure 59, left), varied more than the strain at the coupler locations. When left and right side gage values were averaged (Figure 59, right), the trend was for these strains to increase monotonically with impact speed.

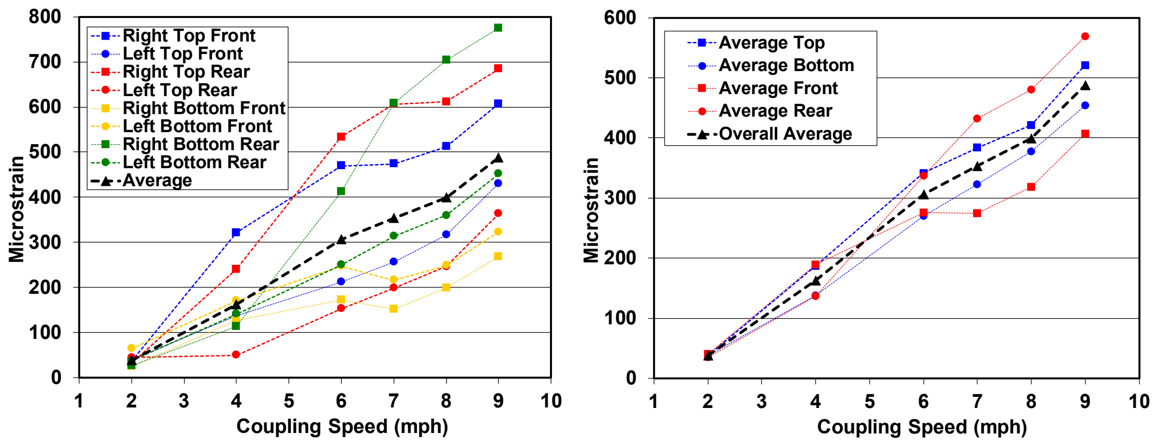

Figure 59. Left: Comparison of peak strains at each of the eight gages placed on the draft pocket side plates, just behind the shear bolts, as a function of impact speed; right: Averaged values for top, bottom, front, and rear locations

The strain levels measured on the thicker sliding lug plates (Figure 60) were significantly less than those measured on the draft pocket side plates. Trends in this data were less obvious, with certain of these strains increasing at low coupling speeds, but decreasing at higher speeds, with the strain having been predominantly tensile.

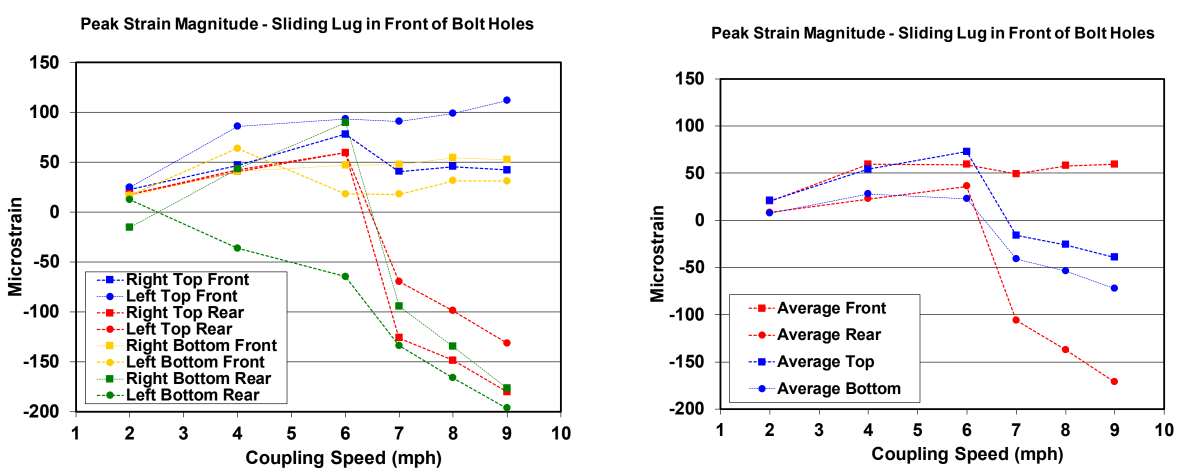

Figure 60. Left: Comparison of peak strains at each of the eight gages placed on the sliding lug side plates, just ahead of the shear bolts, as a function of impact speed; right: Averaged values for top, bottom, front, and rear locations

Finally, peak strain values measured at other positions on the draft pocket side plates and on the web of the locomotive underframe sills are summarized in Figure 61. These strain values appeared to be more consistent left-to-right than those near the shear bolts. They also tended to trend linearly upward with increasing impact speed. They were small, however, with the greatest strain measured at only about 140 microstrain. As is evident, the strain at the two front locations appeared to be compressive, and those at the back two locations appeared to be tensile.

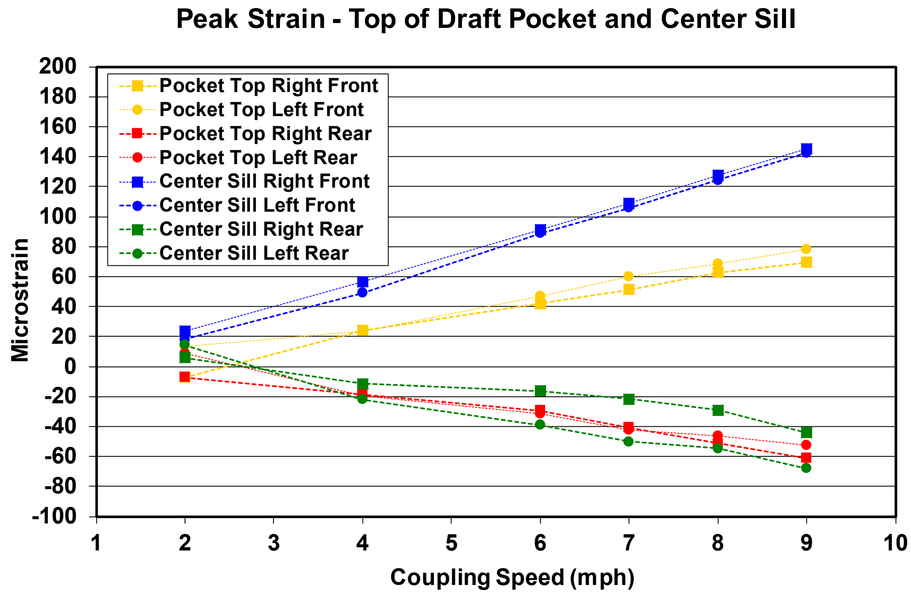

Figure 61. Comparison of peak strains at each of the eight gages placed on the locomotive underframe as a function of impact speed

Prior to the tests, an existing FEA model [14] for simulating a CEM locomotive-to-cab car impact was modified to determine the range of strains that could be expected in a coupling test at 5 mph. The predicted strain distribution in the draft pocket side plate at maximum load for this simulation is shown in Figure 62. While recognizing that the model for the bolted connections were quite simple and that there was a significant gradient in strain behind the bolts, there did appear to be consistency between model predictions and test results. The strain levels were higher behind the top pair of bolt holes than they were behind the bottom pair. Similarly, they were higher along the back column of bolt holes than they were along the front column. In terms of magnitude, FEA results indicated compressive strain levels that ranged from 200 microstrain at the front bolt hole locations (1.5 inches behind the bolt) to 300 microstrain at the rear bolt locations. Results shown in Figure 59 suggested an average strain level of approximately 250 microstrain at this collision speed.

FEA results at the top-front and top-back of draft pocket side plate were consistent with test results shown in Figure 60 in the sense that the predicted strain magnitudes were quite small; ~100 microstrain in compression at the back and only ~10 microstrain in compression at the front. The latter strain value was of opposite sign than the test results, but the magnitude was very small. It was not likely that the model accurately captured the strain distribution at these low levels, especially given the dynamic nature of the impact.

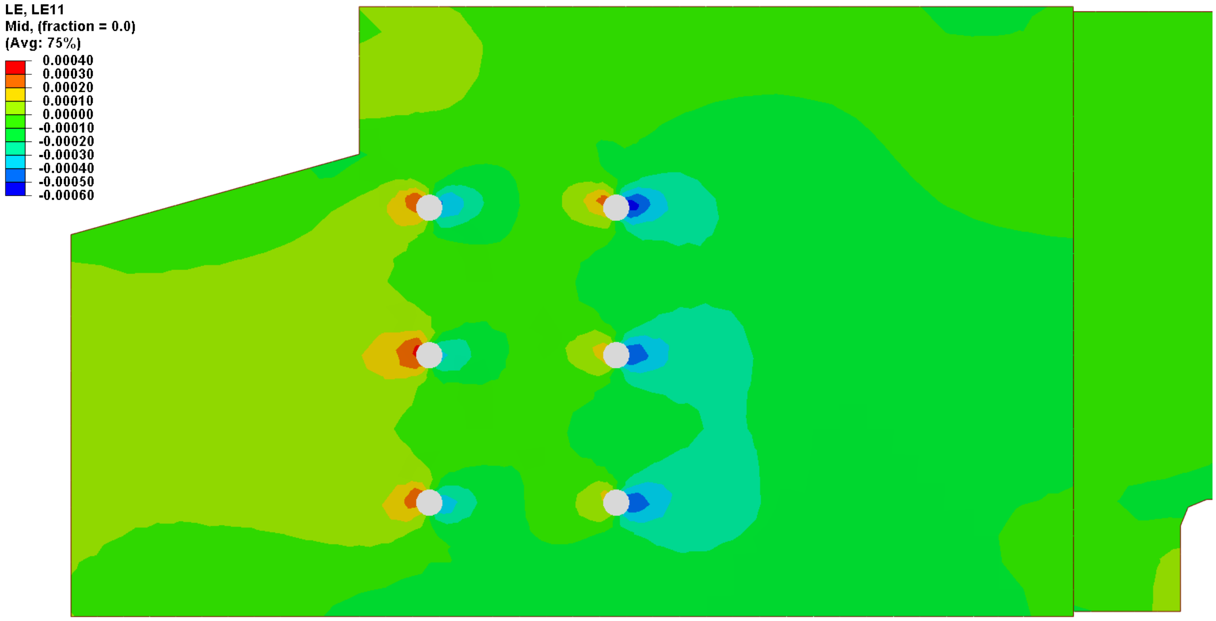

Figure 62. Predicted strain distribution on draft pocket side plate near PBC bolt hole locations for collision of CEM locomotive with cab car at 5 mph

4. Conventional and CEM Coupling Tests: Comparison and Analysis

Industry has raised concerns that PBCs may trigger prematurely, and may require replacement due to unintentional activation as a result of service loads. PBCs are designed with trigger loads greater than the expected maximum service loads experienced by conventional couplers. Analytical models are typically used to determine these trigger loads. Two sets of coupling tests were conducted to demonstrate this, one with a conventional locomotive equipped with conventional draft gear and coupler, and another with a conventional locomotive retrofit with a PBC. Together these tests allowed a performance comparison of a conventional locomotive with a CEM-equipped locomotive during coupling.

4.1 Coupling Tests Comparison

In the conventional coupling tests, a total of six impact tests were conducted, with the final test conducted at a target speed of 12 mph. All actual speeds were within ±0.3 mph of the corresponding target speed. In all but the last two tests (10 mph and 12 mph), the vehicles coupled together at impact. The vehicles remained on the tracks for all of the conventional coupling tests. In the CEM coupling tests, a total of six impact tests were conducted at target speeds of 2 mph, 4 mph, 6 mph, 7 mph, 8 mph, and 9 mph. The test was repeated and the coupling speed was increased for each subsequent test until the PBC triggered. All actual speeds were within ±0.4 mph of the corresponding target speed for these tests. The coupling speed at which the PBC triggered was 9 mph, a speed much greater than typical coupling speeds. In only the first two tests (2 mph and 4 mph), the vehicles coupled together at impact. The vehicles remained on the tracks for all of the CEM coupling tests. Table 5 summarizes the test speeds and coupling of both sets of tests. The target speeds (2 mph, 4 mph, and 6 mph) were the same for the first three tests for each series of tests. The actual test speeds were all within 10 percent of the target speeds for all tests.

Table 5. Coupling tests: Target speeds vs. test speeds

Test No.	Conventional: Test Speed (mph)	Conventional: Vehicles Coupled?	CEM: Test Speed (mph)	CEM: Vehicles Coupled?
1	1.9	Yes	1.8	Yes
2	3.9	Yes	3.7	Yes
3	5.7	Yes	5.7	No
4	7.9	Yes	6.8	No
5	10.0	No	7.6	No
6	11.9	No	8.9	No

One difference between the coupling tests was that the vehicles coupled together in the 2 mph, 4 mph, 6 mph, and 8 mph conventional equipment tests, but only in the 2 mph and 4 mph tests in the CEM tests. This is very likely due to the vertical misalignment in the couplers for the CEM tests. In the conventional coupling tests, the vehicle couplers were aligned vertically. However, in the CEM coupling tests, the vehicle couplers were initially misaligned by approximately 3 inches. This was alleviated somewhat by the M1 coupler being shimmed for the tests. The shims did not completely correct the misalignment, but brought the couplers to within 2 inches of each other vertically.

4.2 Equipment Damage Comparison

In the conventional coupling tests, after all six impacts, the only damage to the locomotive was a small chip on the coupler knuckle that occurred in the 10 mph impact. Damage to the M1 began in the 4 mph impact. Both of the traction bars (which were smaller in diameter than the original traction bars) on the front truck of the M1 bent as a result of the coupling impact. They were replaced with traction bars salvaged from another retired M1. In the 6 mph coupling impact, dimpling of the carbody shell began to occur at the front-left side sill truck connection, as shown in Figure 63. This dimpling increased in size after the 8 mph coupling impact. After the 10 mph impact, the vehicles did not couple, and there was bulging of the M1 draft sill and damage to the coupler stops due to loads imparted by the coupler shank. There was a bend in the right flange of the draft pocket, and one of the buff plates in the draft gear was bent. Buckling of the left side sill truck connection also occurred, with dimpling beginning to occur on the right side sill truck connection. In the 12 mph impact, coupling did not occur. A fragment broke off the front-left truck connection, an underframe member was bent near the front left truck, and the front belt loop of the front truck was severed. There were cracks in both side sills at the front truck connection and significant buckling of the left side sill at that location. Post-test inspection of the M1 draft gear revealed bent buff plates and bent interior draft pocket longitudinal members.

Figure 63. Conventional coupling test: Dimpling of M1 shell at front left side sill truck connection after 5.7 mph impact test

In the CEM coupling tests, after all six impacts, the only structural damage to the locomotive was the triggering of the PBC in the 9 mph impact, with approximately 5/8 inch of stroke experienced by the PBC. This damage can be seen in Figure 64. The front truck transom bar hit the PBC flag and slightly bent its bolt in the 6 mph impact, but did not trigger the PBC. The front truck transom bar continued to strike the PBC flag in subsequent impacts, but did not cause it to release until the PBC triggered in the 9 mph impact. The interference between the transom bar and the PBC flag does not affect the operation or triggering of the PBC. The PBC can only be triggered by a longitudinal force applied to the knuckle end.

Figure 64. Cracked paint on the left side of the PBC deformation tube indicating tube crush

In terms of damage to the M1 in the CEM coupling tests, after the 6 mph impact, the traction rod on the front left truck bent. It was replaced for the 7 mph test, bent again, and was not replaced for the subsequent tests. After the 8 mph test, there was damage at the front-left truck connection, which was very similar to the damage at the front left truck connection in the 12 mph conventional coupling test, as shown in Figure 17. The M1 side sills did not experience the severe dimpling and subsequent buckling that occurred in the conventional coupling tests. However, this was due to the lower impact speeds of the CEM coupling tests.

4.3 Test Measurements

Figure 65 compares the test results for conventional coupling tests with those of the CEM coupling tests. The figure shows the impact force with respect to impact speed for both series of tests. The results were almost identical for impact speeds of less than 6 mph. However, the results diverged at impact speeds greater than 6 mph. This was due to the draft gear system on the Voith PBC design on the CEM locomotive. The draft gear effectively limited the impact force until the PBC was triggered at 9 mph.

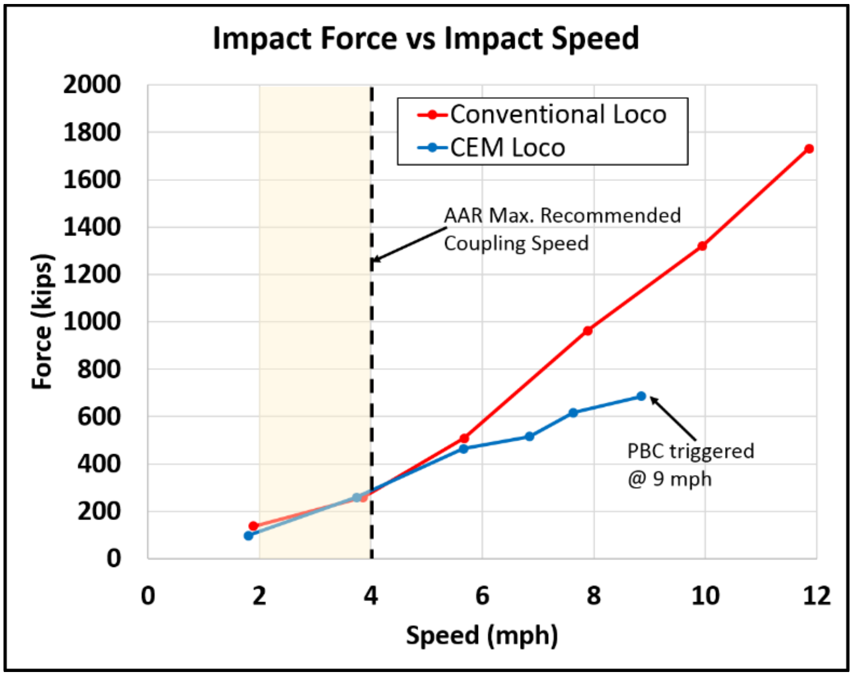

Figure 65. Impact force vs. impact speed comparison

In common practice, railroads typically couple vehicles at speeds between 2 mph and 4 mph, shown as the yellow shaded area in Figure 65. These results showed that the PBC behaved very much like the conventional coupler for the complete range of typical coupling speeds. Note that triggering of the PBC occurred at a speed much greater than the 4 mph maximum coupling speed recommended by the Association of American Railroads [15], shown as the vertical, black-dashed line in Figure 65. Additionally, the likelihood of coupling became less likely at the higher coupling speeds.

The CEM coupling tests successfully demonstrated the force level at which the PBC is designed to trigger. The PBC triggered at a force of approximately 670 kips, as predicted. The impact speed required to trigger the PBC was higher than previously predicted. However, this prediction was based on higher vehicle weights and a softer elastic characteristic of the draft gear in the Voith PBC. The CEM coupling tests showed that for the given vehicle-to-vehicle coupling scenario, it is unlikely that the PBC will trigger within the common coupling speed range recommended by AAR. Additionally, the PBC has a conservative tolerance for overspeed coupling. Computer models can be used to extrapolate and determine coupling speeds for other coupling scenarios. Most PBC manufacturers utilize modeling and testing to design and ensure their PBC will not trigger in coupling scenarios defined by the purchaser. Additionally, the draft gear components of the PBC can be designed to have a higher elastic capacity for cushioning higher-speed coupling events to protect the PBC from premature activation.

5. Conclusion

FRA, with support from the Volpe Center, is conducting research on the implementation of CEM features on locomotives. These features include PBCs and deformable anti-climbers. A series of tests is being conducted, including coupling tests, vehicle-to-vehicle impact tests, and a train-to-train collision test. This arrangement of tests allows for comparison of conventional and CEM-equipped locomotives measured performance during service loading, impacts with varying equipment profiles and train-to-train collisions. Additionally, this arrangement of tests allows for evaluation of the CEM-equipped locomotive performance, as well as comparison of measured with simulated locomotive performance in the car-to-car and train-to-train impact tests.

The first set of tests included coupling tests of a conventional F40 with a Budd M1 cab car. The second set of tests included coupling tests of an F40 retrofit with a CEM system with an M1 cab car. The CEM system was comprised of a PBC, and a DAC, though in coupling tests, the DAC did not play a role.

Concerns have been raised in discussions with industry (e.g., at APTA Passenger Rail Equipment Safety Standards meetings, ASME conferences, AAR meetings) that PBCs may trigger prematurely, and may require replacement due to unintentional activation as a result of service loads. PBCs are designed with trigger loads greater than the expected maximum service loads experienced by conventional couplers. Analytical models are typically used to determine these required trigger loads for the purchasing railroad. The two sets of coupling tests were conducted to demonstrate this, one with a conventional locomotive equipped with conventional draft gear and coupler and another with a conventional locomotive retrofit with a PBC.

The conventional coupling tests established a baseline for comparison with the CEM coupling tests. The objective of the conventional coupling tests was to measure and characterize the structural performance of the conventional coupler and the coupling vehicles under a range of increasing dynamic coupling speeds to determine when damage occurred in the coupler system. Computer simulations of the impacts were conducted prior to the tests and served to inform the testing decisions. In the tests, equipment damage began to occur at 6 mph. Researchers predicted that damage would occur for coupling speeds between 6 and 8 mph. The test results compared favorably with the pre-test predictions and confirmed that coupling speeds should be kept under 6 mph to prevent equipment damage.

After the conventional coupling tests, a CEM system was retrofit to an F40 locomotive and a series of dynamic CEM coupling tests was conducted. The primary objective was to demonstrate the robustness of the PBC design and determine the impact speed at which PBC triggering occurred. Measurements were made to characterize the structural performance of the PBC and the coupling vehicles under a range of increasing dynamic coupling speeds until damage occurred in the coupler system. The test results compared favorably with the pre-test predictions for the coupling force at impact. Additionally, the pre-test modeling predicted that damage would occur in the M1 truck-to-carbody connection at speeds above 5 mph. This was confirmed in the tests.

CEM coupling tests also successfully demonstrated the force level at which the PBC was designed to trigger. In the test, the PBC triggered at just under 9 mph. With corrected masses and the idealized PBC characteristic updated after the conduct of the test, a post-test collision dynamics model estimated that the PBC triggered between 8 and 9 mph. The CEM coupling tests showed that for the given vehicle-to-vehicle coupling scenario, it was unlikely that the PBC would trigger within the common coupling speed range. The test results also highlight that the draft gear can be designed to give more margin against unintentional PBC triggering during overspeed coupling.

Certain aspects of the strain gage data were analyzed. Researchers found that the force through the two coupler locations were remarkably consistent with one another and indicate an effectively linear increase in coupler force with impact speed. For lower coupling speeds, these strain gage-based estimates of force were also consistent with acceleration-based estimates of force. For higher coupling speeds, the agreement was not as good, which may be because the dynamics of the impact at these higher speeds do not lend themselves to estimates that assume that the entire mass of the vehicle is decelerating uniformly.

The test results for the conventional coupling tests were compared with those of the CEM coupling tests. The impact force with respect to impact speed for both series of tests were almost identical for impact speeds of less than 6 mph. However, the results diverged at impact speeds greater than 6 mph. This was due to the design of the draft gear system on the Voith PBC on the CEM locomotive. The draft gear effectively limited the load of the impact until the PBC was triggered at 9 mph.

The results showed that the PBC behaved very much like the conventional coupler for the complete range of typical coupling speeds. Notably, triggering of the PBC occurred at a speed much greater than the maximum coupling speed recommended by the Association of American Railroads (4 mph). Additionally, coupling of the two vehicles became less likely at the higher coupling speeds. Computer models can be used to extrapolate and determine coupling speeds for other coupling scenarios. Most PBC manufacturers utilize modeling and testing to design and ensure their PBC will not trigger in coupling scenarios defined by the purchaser. Additionally, the draft gear components of the PBC can be designed to have a higher elastic capacity for cushioning higher speed coupling events to protect the PBC from premature activation.

The planned next steps in this research are to conduct additional full-scale dynamic tests which will accomplish the objectives of demonstrating that the locomotive CEM system performs well in service, provides crashworthiness compatibility with a range of equipment, and exhibits increased crashworthiness over conventional equipment. The planned tests are designed to incrementally evaluate how a CEM system can improve performance of a locomotive in a head-on collision scenario in which a locomotive-led train collides with a stationary train. The stationary train can be led by a conventional locomotive, a CEM locomotive, a cab car, or a freight car.

The next test will be the second vehicle-to-vehicle impact test of a CEM F40 (retrofit with a PBC and a DAC) impacting a different stationary vehicle. These tests will demonstrate that the components work together as an integrated system to provide improved crashworthiness with a range of equipment. The final test planned is a train-to-train impact test of a CEM F40-led train impacting a conventional stationary train, which will demonstrate the effectiveness of the crashworthy components in a consist.

While the overall objective of these tests is to demonstrate the effectiveness of locomotive crashworthiness equipment in a train-to-train collision, the test data will also be used for comparison with analyses and modeling results. The measurements will be used to refine the analysis approaches and models and assure that the factors that influence the response of the equipment are taken into account. Modeling can then be used to extrapolate to other collision scenarios.

6. References

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Abbreviations and Acronyms

Abbreviation or Acronym	Name
AAR	Association of American Railroads
CFC	Channel Frequency Class
CEM	Crash Energy Management
DAC	Deformable Anti-Climber
F40	F40 Locomotive
FRA	Federal Railroad Administration
M1	Budd M1 Cab Car
PBC	Push-Back Coupler
TTC	Transportation Technology Center (the site)
TTCI	Transportation Technology Center, Inc. (the company)
Volpe Center	Volpe National Transportation Systems Center