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LOCOMOTIVE CRASH ENERGY MANAGEMENT COUPLING TESTS

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ABSTRACT

Research to develop new technologies for increasing the safety of passengers and crew in rail equipment is being directed by the Federal Railroad Administration's (FRA's) Office of Research, Development, and Technology. Crash energy management (CEM) components which can be integrated into the end structure of a locomotive have been developed: a push-back coupler and a deformable anti-climber. 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 push-back couplers may trigger prematurely, and may require replacement due to unintentional activation as a result of service loads. Push-back couplers (PBCs) are designed with trigger loads meant to exceed the expected maximum service loads experienced by conventional couplers. Analytical models are typically used to determine these required trigger loads. Two sets of coupling tests have been 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 push-back coupler. 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, car-to-car compatibility tests of CEM-equipped locomotives, as well as a train-to-train test are also planned. 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 tests.

The coupling tests of a conventional locomotive have been conducted, the results of which compared favorably with pre-test predictions. This paper describes the results of the CEM-equipped locomotive coupling tests. In this set of tests, a moving CEM locomotive was coupled to a standing cab car. The primary objective was to demonstrate the robustness of the PBC design and determine the impact speed at which PBC triggering occurs. The coupling speed was increased for each subsequent test until the PBC triggered. The coupling speeds targeted for the test were 2 mph, 4 mph, 6 mph, 7 mph, 8 mph, and 9 mph. The coupling speed at which the PBC triggered was 9 mph. The damage observed resulting from the coupling tests is described. Prior to the tests, a lumped-mass model was developed for predicting the longitudinal forces acting on the equipment and couplers. The test results are compared to the model predictions. Next steps in the research program, including future full-scale dynamic tests, are discussed.

BACKGROUND

The Office of Research, Development, and Technology of the Federal Railroad Administration (FRA) and the Volpe Center are continuing 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 [1, 2, 3], and in light of the success of crash energy management technologies in passenger trains [4], FRA seeks to evaluate the effectiveness of components that are 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 [5].

A research program has been conducted that developed, fabricated and tested two crash energy management (CEM) components for the forward end of a locomotive: (1) a deformable anti-climber, and (2) a push-back coupler [6, 7]. Detailed designs for these components were developed, and the performance of each design was evaluated through large deformation dynamic finite element analysis (FEA). Two test articles were fabricated and individually dynamically tested by means of rail car impact into a test wall in order 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 finite element model predictions in terms of energy absorption capability, force-displacement behavior and modes of deformation.

This research program integrates the two CEM components onto a locomotive in order to demonstrate that these components work together to mitigate the effects of a collision and prevent override [8]. A series of dynamic CEM coupling tests was performed to demonstrate that the push-back coupler will, or will not, trigger, depending on the proper conditions. However, before demonstrating the robustness of the push-back coupler, 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 [9], [10]. The results of the conventional coupling tests compared favorably with pre-test predictions. The lowest coupling speed at which damage occurred was 6 mph.

The CEM coupling tests were conducted repeatedly with the same F40 locomotive and M1 passenger car, with targeted impact velocities of 2 mph, 4 mph, 6 mph, 7 mph, 8 mph, and 9mph, or until the PBC triggered. The test requirements and pre-test analysis for these tests are detailed in a companion paper [11]. This paper describes the test setup, equipment, retrofit of the F40 locomotive, test implementation, and test results. The results of the tests are then compared to the pre-test analysis. The paper concludes with a summary evaluation and the next steps in the research program.

TEST SCENARIO: COUPLING IMPACT

The CEM coupling tests were conducted at the Transportation Technology Center (TTC) in Pueblo, Colorado on October 3-4, 2017. The two CEM components, a deformable anti-climber (DAC), and a push-back coupler (PBC), were retrofit onto an F40 locomotive. Details of the fabrication and retrofit can be found in a previous companion paper [11].

Test Setup

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, 4mph, 6mph, 7mph, 8mph, and 9mph, or until the PBC triggered, as shown schematically in Figure 1. 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. 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.

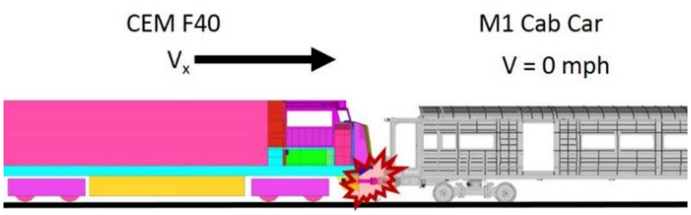

Figure 1. Schematic of CEM coupling test initial conditions.

The primary objective was to demonstrate the robustness of the PBC design and determine the impact speed at which PBC triggering occurs. The structural performance of the PBC and the coupling vehicles were measured and characterized under a range of dynamic coupling speeds until 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 includes 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, there was difficulty in inspecting the 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 of the paper.

Equipment

The equipment used in the CEM coupling tests were retrofit F40 locomotive No. 234, and M1 passenger cab car No. 8221, shown in the pre-test photograph of Figure 2. Figure 3 shows the DAC and PBC retrofit to the F40 locomotive. These two components comprise the CEM system. Figure 4 shows the PBC installed within the sliding lug, and Figure 5 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 is triggered at approximately 680 kips. Once the fuse 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 slide 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 have the colliding vehicle ends 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 [5], [6], [7].

Figure 2. Pre-test photos of M1 cab car No. 8221 (left) and F40 locomotive No. 234 (right) used in the CEM coupling tests.

Figure 3. The DAC (top) and the PBC (bottom) comprise the locomotive CEM system.

Figure 4. PBC installed within the sliding lug.

Figure 5. Exterior view of the shear bolts installed through the draft pocket.

Instrumentation

Measurements were made with accelerometers, strain gages, displacement transducers, and high speed video cameras. This instrumentation was intended to capture 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 6 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 three dimensional gross motions of the carbody – longitudinal, lateral, and vertical accelerations, as well as yaw, pitch, and roll.

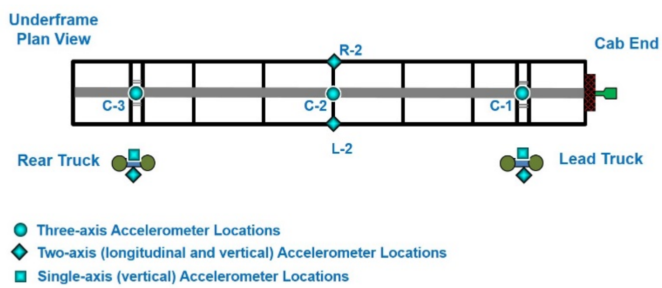

Figure 6. Schematic illustration of M1 cab car accelerometer locations

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% 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.

TEST RESULTS

Table 1 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 1. 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 several Volpe and TTCI personnel to look for structural damage resulting from the impact. The vehicles coupled in the first two tests (2 mph & 4 mph), but not in the higher speed impacts. The PBC triggered during the 9mph test.

Tests 1 & 2: 2 mph & 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.

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 7. 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 locomotive. 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 8) 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 9. This traction rod was replaced before the next test, the 7 mph impact.

Figure 7. The vehicles did not couple in the 6mph impact.

Figure 8. Front transom bar of locomotive hit PBC flag.

Figure 9. M1 front left traction rod deformed after 6mph test.

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 locomotive. However, as a result of the impact, the front truck transom bar of the locomotive contacted the PBC again. Figure 10 shows the space between the rear of the draft pocket and the transom bar. The PBC flag can 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 10. PBC flag and transom bar after 7mph 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 bent again by the impact, as shown in Figure 11. This traction rod was not replaced and was left as is for the remaining tests, as there were no more replacements.

Figure 11. New M1 front left traction rod deformed again after 7mph test.

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 locomotive. However, again as a result of the impact, the front truck transom bar of the locomotive contacted the PBC. Figure 12 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 is slightly bent, but still attached to the PBC, as shown in Figure 13.

Figure 12. PBC flag and transom bar after 8mph impact.

Figure 13. Close-up of the PBC flag and bolt after 8mph 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 even more by the impact, as shown in Figure 14. 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 15. 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 15.

Figure 14. M1 front left traction rod deformed more after 8mph test.

Figure 15. Piece broken off of M1 front left truck, with piece held up to its former place (left).

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 16 shows the PBC flag detached from the PBC and hanging underneath the draft pocket. The flag is attached to the PBC by a bolt that shears when the crush of the deformation tube is initiated. This allows the flag to fall away from the PBC, indicating that tube crush has been initiated. Figure 17 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 robustness in the design.

Figure 16. PBC flag detachment indicates the PBC was triggered.

Figure 17. The PBC trigger indicator is an orange flag that is 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 18 (right side) and Figure 19 (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.

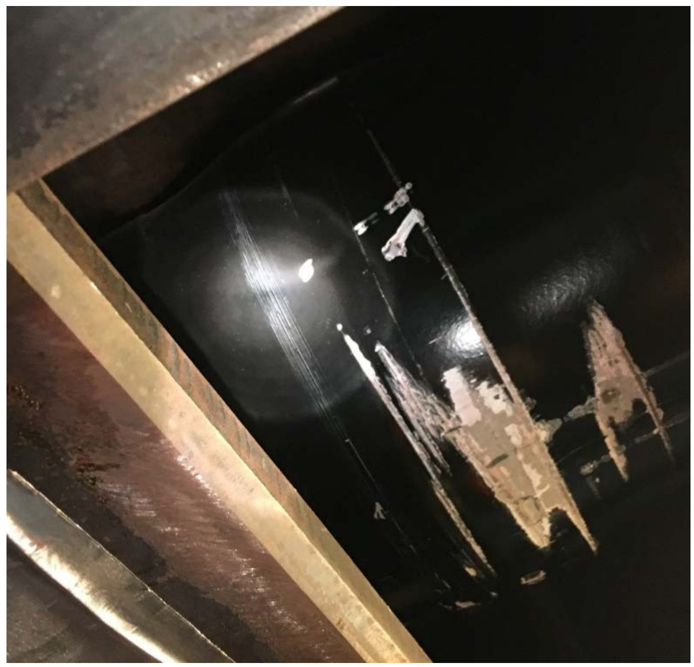

Figure 18. Cracked paint on the right side of the PBC deformation tube indicating tube crush.

Figure 19. 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 20. It is important to note that there was no deformation to the side sills at the connections to the front truck. This is markedly different from what occurred in the conventional coupling tests, where there was extensive deformation, and eventually fracture, in the side sills at the connections to the front truck [10].

Figure 20. M1 front left traction rod deformed more after 9mph test.

Damage to Draft Systems

A post-test teardown of the vehicle draft gear systems will be performed to determine the internal damage sustained by the vehicles as a result of the six impact tests. A thorough inspection of the F40 locomotive PBC, sliding lug, and draft pocket will be conducted, as well as a thorough inspection of the M1 draft gear and draft pocket. The inspection of these vehicles had not yet occurred at the time of the writing of this paper.

Test Data

The test data were filtered using a channel frequency class (CFC) 60 filter consistent with the requirements of SAE J211. 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 2. The locomotive carbody accelerometer data were used in these calculations.

Table 2. Impact Forces & 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

TEST ANALYSIS

Prior to the test a simplified lump-mass model was created to estimate the speed at which the PBC would trigger [11]. This model estimated the PBC force-displacement behavior and utilized typical vehicle weights and a typical conventional locomotive draft gear. Figure 21 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 compare favorably with the prediction.

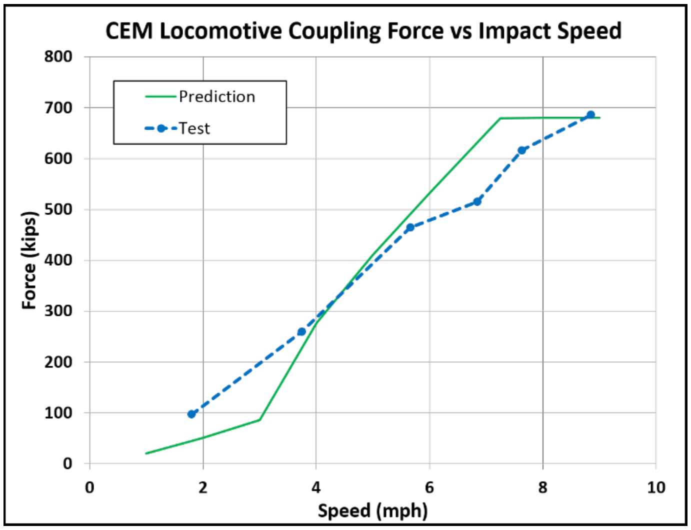

Figure 21. Peak coupling force as a function of impact speed.

However, the model predicted that triggering of the PBC would occur at an impact speed of 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 9. The traction rod experienced bending in the 5.7 mph test as well as 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 22 shows an idealized representation of the force-displacement behavior of the Voith PBC retrofitted onto the F40. This characteristic does not include the contribution of the DAC in the collision. The PBC draft gear characteristic has 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 lb and the M1 cab car weighed 89,700 lb. With the correct masses and the idealized PBC characteristic updated after the conduct of the test, a post-test collision dynamics model estimates that the PBC triggers between 8 and 9 mph. This estimate is closer to what occurred in the tests than the original pre-test prediction.

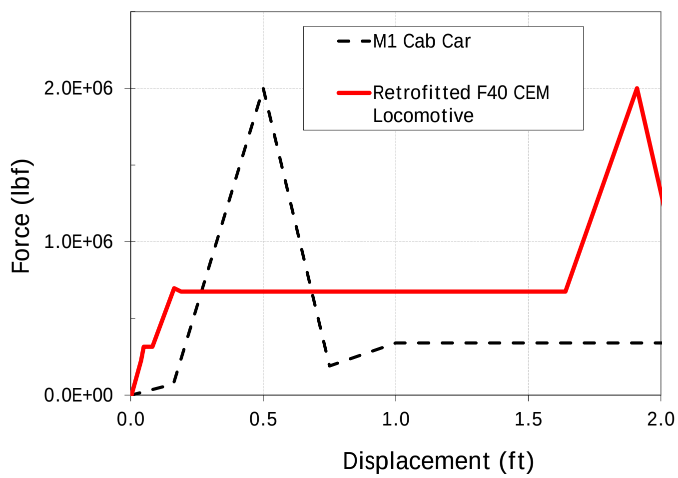

Figure 22. Idealized force-displacement characteristics of colliding vehicles.

During the series of impact tests the colliding equipment coupled at speeds below 5 mph. The pre-test collision dynamics model assumes that the colliding equipment collides and remains 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 in the model agreement.

SUMMARY & CONCLUSIONS

The FRA, with support of the Volpe Center, is conducting research on the implementation of CEM features on locomotives. These features include push-back couplers and deformable anti-climbers. A series of tests are being conducted, including coupling tests, car-to-car 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 coupling. 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.

In the coupling tests of CEM equipment, the coupling speed at which the PBC will trigger was measured. A moving locomotive was coupled to a standing cab car. The coupling speeds targeted for the test were 2 mph, 4 mph, 6 mph, 7 mph, 8 mph, and 9 mph. The coupling speed at which the PBC triggered was 9 mph. These coupling tests of locomotives with push-back couplers demonstrated that push-back couplers do not trigger at typical 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 680 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 stiffer elastic characteristic of the draft gear in the Voith PBC.

In common practice, railroads typically couple vehicles at speeds between 2 mph and 4 mph. These tests show that for the given vehicle-to-vehicle coupling scenario, it is unlikely the PBC will accidently trigger within this common coupling speed range. Computer models can be used to extrapolate and determine coupling speeds for other 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.

NEXT STEPS

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 planned tests are based on 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 overall objective of these tests is to demonstrate the effectiveness of the locomotive CEM system, comprised of a PBC and a DAC. The first set of tests were coupling tests of a conventional F40 coupling with an M1. The second set of tests, described in this paper, were coupling tests of an F40 retrofit with a PBC coupling with an M1 cab car. This arrangement of the tests allows comparison of the conventional coupler performance with the performance of the PBC. The third set of tests will be vehicle-to-vehicle impact tests of a CEM F40 (retrofit with a PBC and a DAC) impacting a stationary vehicle. The final set of tests are planned to be train-to-train impact tests of a CEM F40-led train impacting a conventional stationary train.

Table 3 summarizes the critical measurements for each of the four types of tests. The first two sets of tests, the coupling tests, demonstrated that the PBC performs as expected in service. The vehicle-to-vehicle tests will demonstrate that the components work together as an integrated system to provide crashworthiness with a range of equipment, and the train-to-train tests will demonstrate the effectiveness of the crashworthy components.

While the overall objective of these tests is to demonstrate the effectiveness of locomotive crashworthiness equipment, 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. Table 3 lists the measurements that are critical in assuring the appropriate modeling and analysis of the equipment.

Efforts are underway to prepare for the third series of tests, the vehicle-to-vehicle tests (highlighted in blue in Table 3). An F40 very similar to the one used in the conventional and CEM coupling tests is being prepared for retrofit of the crashworthy components, the PBC and DAC. A stationary car is being chosen and prepared for the tests. The vehicle-to-vehicle tests are projected to occur in 2018.

Table 3. Test descriptions and critical measurements

Test Description	Critical Measurements
Conventional Coupling Tests	• Maximum non-destructive coupling speed • Dynamic impact forces • Impact accelerations • Displacements
CEM Coupling Tests	• Maximum non-destructive coupling speed • Dynamic crush forces • Impact accelerations • Displacements • Effectiveness of PBC
Vehicle-To-Vehicle Tests	• Dynamic crush forces • Accelerations • Displacements • Effectiveness of PBC and DAC working as a system
Train-To-Train Tests	• Effectiveness of crashworthy components at managing load path • Effectiveness of crashworthy components in inhibiting override and lateral buckling

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