Locomotive crashworthiness research

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ABSTRACT
The Federal Railroad Administration (FRA) of the U.S. Department of Transportation conducts research on locomotive crashworthiness. The research approach includes four phases:

1. Accident investigations to assemble sequences of events leading to injury and fatality.
2. Locomotive performance is analyzed, and potential improvements are explored.
3. Specifications are developed, using the research results.
4. Locomotives are designed to the evolved standard and introduced into service.

As technological advances show promise for improved performance, the phases proceed in an evolutionary fashion, with continuous research leading to continuously improving standards and safer designs.

Recent accidents' consequences suggest that locomotives built to the requirements of U.S. Code of Federal Regulations Title 49 Part 229 Appendix E (Appendix E) are often more crashworthy than would be expected of older locomotives. In the 1990s, FRA conducted research in response to the Rail Safety Enforcement and Review Act of 1992. In 1997, at the request of the FRA, the Locomotive Crashworthiness Working Group was formed. Members of the working group included railroads, suppliers, and labor organizations. Further research was conducted and Appendix E was drafted and recommended to FRA. After the Working Group disbanded, FRA continued research on locomotive crashworthiness. Recently component tests were conducted of energy-absorbing anti-climbers and couplers. Full-scale impact tests are being planned, in part to show crashworthiness compatibility of modified locomotives with a range of freight and passenger equipment. Results of this research are currently being used by the Liquefied Natural Gas (LNG) Tender Technical Advisory Group of the Association of American Railroads (AAR) to develop crashworthiness requirements for LNG tenders and locomotives.

1 INTRODUCTION

The Federal Railroad Administration (FRA) Office of Research, Development, and Technology conducts research on the full range of railroad safety topics. This research includes advancing and enhancing technologies for rail equipment safety and facilitating their implementation in the railroad industry. Work is done to identify safety concerns, such as assessing the likelihood and damage resulting from accidents and the development of accident scenarios of concern. Safety strategies for mitigating the consequences of the scenarios, including development of technologies for improved occupied volume protection, injury prevention, fuel containment, and glazing impact resistance. This research produces the information needed to understand and apply the technology to the rail industry. The information may then be used to engineer equipment and verify its performance, inform policy decisions, and support standards development.

A timeline of selected accidents, noteworthy documents, and locomotive crashworthiness research activities is shown in Figure 1. The continued occurrence of train accidents has motivated the government and industry to strive to provide adequate locomotive crashworthiness. In the 1970s and 1980s, the National Transportation Safety Board (NTSB), an agency of Congress, investigated a number of train accidents which resulted in recommendations for increased locomotive crashworthiness (1, 2, 3, 4). These recommendations led the Association of American Railroads (AAR), an industry organization, to issue Locomotive Crashworthiness Standard S-580 (5) and Congress to request FRA's assessment of locomotive crashworthiness (6). FRA then went onto develop crashworthiness regulations, from recommendations made by an FRA-led government-industry committee, the Railroad Safety Advisory Committee (RSAC) (7). RSAC was formed in 1996 to develop recommendations for improving railroad safety, taking advantage of the Federal Advisory Committee Act of 1972. In parallel, the AAR revised S-580 based on recommendations of RSAC (8). In 2012, Amtrak petitioned FRA to accept an alternative crashworthiness standard for the Siemens-built ACS-64 (9). This alternative standard was developed from criteria and procedures for passenger trainsets with crash-energy management features (10) and dynamic load requirements for passenger cab car end frames (11). Currently, AAR is developing standards for Liquified Natural Gas (LNG) fuel tenders.

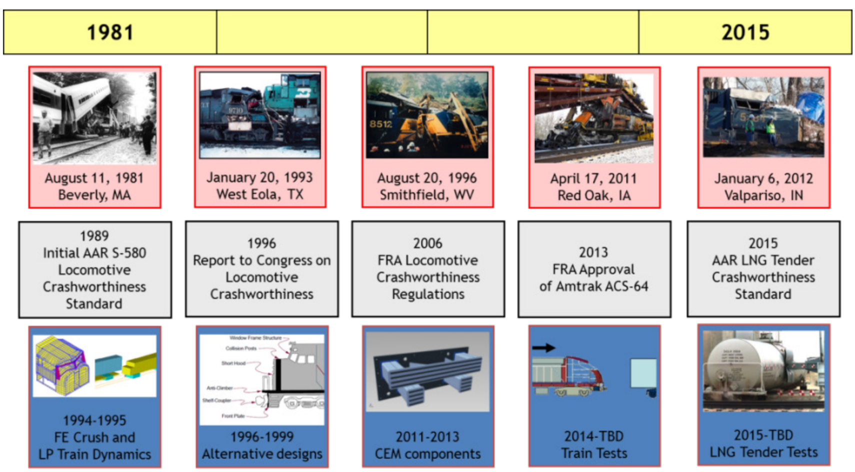

Figure 1. Timeline of selected accidents, noteworthy documents, and locomotive crashworthiness research activities

FRA has been continuously conducting research on locomotive crashworthiness since the mid-eighties. To support FRA's response to the U.S. Congress, research on locomotive crashworthiness was conducted. This research led to the development of finite-element analysis techniques for evaluating the crush behavior of locomotive structures and lumped-parameter analysis techniques for evaluating the collision-trajectories of the locomotives and cars that make up trains (12). Follow-on research was conducted to help support the development of the current FRA regulations and industry standards (13, 14, 15, 16). This research focused on strategies for improving locomotive crashworthiness. Subsequently, additional research was conducted to further refine locomotive analysis techniques (17, 18) and to explore further improvement strategies (19, 20, 21, 22). FRA research on passenger equipment crashworthiness was used by Amtrak in submitting its petition for an alternative crashworthiness standard for the Siemens-built ACS-64 (9). FRA research results are being made available to AAR, to help support development of LNG locomotive and fuel tender crashworthiness standards.

2 FRA CRASHWORTHINESS RESEARCH AND INDUSTRY PARTICIPATION

The approach taken in locomotive crashworthiness research is to identify problematic areas from accident investigations, to develop alternative strategies for addressing the problems, to compare the effectiveness of the alternatives and traditional strategies, and to support implementation of effective crashworthiness strategies. When the NTSB identified deficiencies in locomotive crashworthiness, the effectiveness of modified collision posts, short hoods, anti-climbers, and window structures were subsequently evaluated. As the research was conducted, the results were shared with RSAC Locomotive Crashworthiness Working Group and documented in technical papers and reports. The working group used this information to inform development of industry standards and recommendations for FRA regulations. The influences of the new standards were reflected in the next generation of rail equipment. This cycle of research and application of results is illustrated in Figure 2. This cycle has four facets:

1. Accidents are investigated to estimate the sequence of events leading to injury and fatality.
2. The performance of conventional equipment is analyzed, and potential improvements are analytically explored. Conventional and improved designs are tested, and the results compared to determine the potential degree of improvement.
3. The results of the accident investigations, analyses, and testing are used to help develop specifications and standards
4. Improved equipment is designed according to the evolving standards, and introduced into service.

These facets constitute an evolutionary cycle, in which continuous research leads to continuously improving standards and safer designs.

Figure 2. Engineering research approach to locomotive crashworthiness

3 CURRENT PRACTICES

The generation of locomotives compliant with the current FRA crashworthiness regulations has been in service sufficiently long that the cycle is repeating. While there seems to be general agreement among government, industry, and labor that locomotives compliant with current standards are more crashworthy than older locomotives, there appears to be room for improvement. As part of the results of its investigation of the Red Oak accident, the NTSB has recently issued recommendations for further improvement of locomotive crashworthiness (23). In a 23 mph collision with maintenance-of-way equipment, the two locomotive cab occupants were fatally injured.

3.1 Regulations and standards

Locomotive crashworthiness in the U.S. is governed by FRA regulations and AAR standards. The FRA regulations in Appendix E (24) are performance-based, while the AAR standards in S-580 (8) are design-based. Performance-based requirements include impact scenarios that are intended to bound the range of potential accidents and incidents. Compliance can typically be demonstrated with computer simulations, non-destructive car tests, and destructive component tests. Performance standards permit a wide range of design approaches. Design-based requirements include static loads that are intended to result in particular design features. These features are expected to be effective in the range of expected accident and incident conditions. Compliance can typically be demonstrated with classical manual engineering calculations and non-destructive tests. Design standards often implicitly assume a particular design features, such as buff stops. These and other loads, described in detail in S-580, are intended to provide the same level of crashworthiness for a traditionally-designed North American locomotive as the performance-based federal regulations (7).

There are two scenario prescribed in Appendix E (24). These scenarios are shown schematically in Figure 3. In both scenarios, the locomotive is impacted by an idealized proxy object at a prescribed speed. In the first scenario, the proxy object impacts the full width of the locomotive. In the second scenario, the proxy object impacts the corner of the locomotive. The outcome of both scenarios must not result in more than 305 mm of intrusion into the cab, the occupied space of the locomotive.

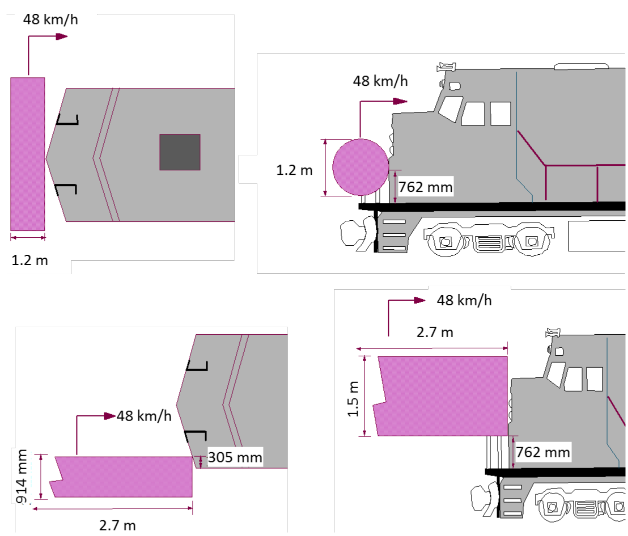

Figure 3. Schematics adapted from Appendix E locomotive impact scenarios

There are many load cases prescribed in AAR S-580. These include load cases for the underframe and collision posts. Briefly, the underframe is required to support a load of 4.45 MN when loaded on the buff stops. (The buff stops are a design feature necessary to support the draft gear and coupler system typically used on U.S. railroads.) The underframe must support this load without any permanent deformation. Compliance can be shown with a non-destructive quasi-static test, first loading the underframe and then carefully inspecting it. Collision posts must be able to sustain loads of 3.34 MN at the attachment to the underframe and 2.23 MN at a height 762 mm above the underframe. The short hood must be able to support a load of 1.78 MN applied to the upper corner of the short hood over an area that is 305 mm wide and 762 mm tall.

In addition to FRA Appendix E and AAR S-580, FRA regulations allow petition for approval of alternative locomotive crashworthiness designs. Amtrak petitioned FRA for such approval of the ACS-64 electric locomotive (9). This locomotive was designed and manufactured by Siemens, based on its Vectron locomotive platform design. The crashworthiness aspects of this locomotive were designed to scenarios adapted from the grade-crossing collision scenarios described in U.S. Code of Federal Regulations Title 49 Part 238 Appendix F (11) and the train-to-train collision scenario described in a criteria and procedures report (10). This petition was accepted by FRA after careful review.

3.2 Selected accidents showing strengths and room for improvement of current practice

On January 6, 2012, there was a train accident involving three freight trains in Valparaiso, Indiana (25). None of the crew members of the three trains were fatally injured. All three trains were initially travelling in the same direction, westbound. While travelling at approximately 43 mph, the lead locomotive of the second train collided with the trailing tank car of the stopped train. During the collision, the lead locomotives of the second train derailed onto the adjacent track. Shortly after coming to rest, the lead locomotive of the third train collided with the derailed locomotives of the second train. The third train was travelling approximately 50 mph when it collided with the derailed locomotives of the second train. A photograph of the accident is shown in Figure 4, with the locomotives from the first train on the left and near the middle, and a locomotive from the first train toward the right. The crashworthiness of the locomotives, all of which were designed to AAR S-580 and to Appendix E, is believed to have helped the crew members survive.

Figure 4. Photograph of Valparaiso accident (24)

On April 17, 2011, a freight train travelling at 23 mph collided with the rear of a standing maintenance-of-way equipment (MoW) train (23). Both crew members on the freight train were fatally injured. The crew members of the thirty-five car MoW train were on the locomotive at the head end, and were not fatally injured. As seen in Figure 5, 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. While deformed, the anti-climber and collisions posts remained essentially intact. The initial conditions of this accident appear to be within the range intended for current locomotive crashworthiness requirements.

Figure 5. Photograph of Red Oak accident

4 ONGOING RESEARCH

4.1 Crash Energy Management

As shown by the Red Oak accident, locomotives are susceptible to override when they collide with another vehicle, and the consequences can be catastrophic. Research has shown that the addition of structural features to the forward end of a locomotive can greatly reduce the propensity for override (20). These features include:

1. Push-back couplers, and
2. Deformable anti-climbers.

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 or vertical buckling of the vehicles with respect to one another. Deformable anti-climbers manage the load path between the vehicles, deforming gracefully and inhibiting the formation of a ramp.

Push-back coupler and deformable anti-climber proof-of-concept designs have been developed and are being tested (20, 21, 22). These designs were developed for a conventional platform-style locomotive. Computer simulations were used extensively in their development. Component tests have been conducted, and full-scale service and impact tests are planned.

The design for the push-back coupler employs a conventional AAR H-type coupler head with a modified shank attached to a push-back yoke and deformation tube (20). Figure 6 shows a view from below of the push-back coupler inside the draft gear pocket of a locomotive. The draft gear pocket has been redesigned to provide more than 305 mm of additional stroke after the pushback coupler is exhausted. The push-back coupler is attached to the draft gear pocket by the coupler support assembly (shown in yellow in Figure 6) with 12 shear bolts, six on each side. The six shear bolts on the right side are shown in Figure 6 in green. These bolts are designed to fail at a total load of approximately 4.45 MN once the energy-absorbing stroke of the push-back coupler has been exhausted. After the shear bolts fail, the entire coupler support assembly, or 'sliding lug', slides back, so that the load through the coupler is effectively zero. Because the coupler can no longer support a longitudinal load, the load path is shifted to the deformable anti-climber

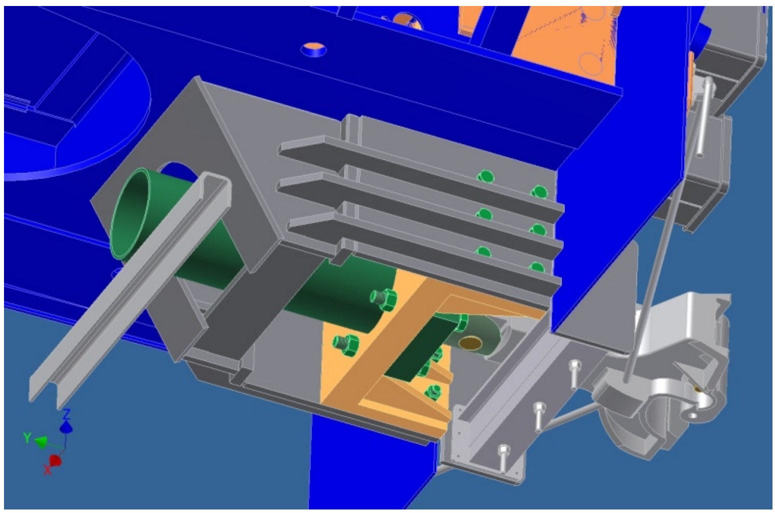

Figure 6. View of the shear bolts (green) that attach the push-back coupler to the sides of the draft gear pocket

The locomotive deformable anti-climber was designed to be effective with a wide range of equipment, including conventional locomotives, conventional passenger-carrying cab cars, and freight cars (20). The design for the deformable anti-climber employs four progressive buckling tubes (crush tubes) welded onto the front plate of the locomotive: two tubes located at the base of the short hood, and two tubes located beneath them. This difference in elevation helps the anti-climber to be effective in impacts with equipment which has a range of underframe heights.

Figure 7 shows a detailed view of the deformable anti-climber/pushback coupler system. In a collision with a conventional locomotive, the upper crush tubes are designed to interact with heavy gussets that are welded to the front plate of the locomotive as part of the conventional anti-climber. The upper crush tubes are connected laterally by a ribbed front plate. In the event of a collision with a cab car, this plate also interacts with the collision posts at the end of the cab car, allowing the upper crush tubes to absorb energy. The lower set of crush tubes is designed to interact with the buffer beam of a colliding cab car. In a collision with a conventional locomotive, these lower tubes do not participate in the early stages of the collision. In a collision with a center beam flat car-type freight car, neither set of tubes participates in the early stages of the collision. Eventually, they interact with the bulkhead of the freight car. Not shown in Figure 7 is support structure which has been added to the locomotive for the purpose of transferring impact loads into the underframe.

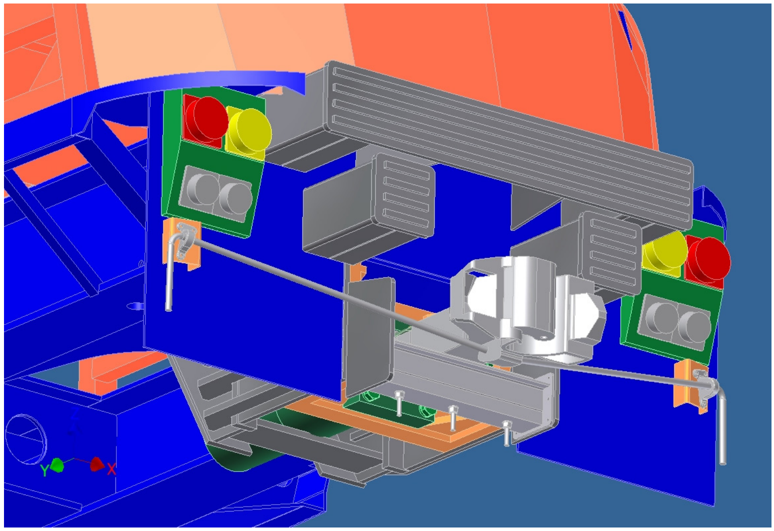

Figure 7. Detailed view of the deformable anti-climber/push-back coupler system

Finite element (FE) models were constructed for the conventional and modified locomotives, a cab car, and a freight locomotive (21). These models were appropriately combined to simulate CEM locomotive collisions with conventional locomotive, a conventional cab car, and a freight car. The simulations showed that the pushback coupler and deformable anti-climber designs met their deformation mode and energy absorption requirements. There was no ramp formation or uncontrolled deformation in the CEM locomotive or conventional vehicles, and, of particular importance, there was no override of one vehicle onto another in any of the collision scenario cases.

Pushback coupler and deformable anti-climber test articles were analyzed, constructed, and tested (22). Finite element models of the test articles were developed and exercised to e predict of the performance of the test articles. Dynamic testing was conducted at TÜV SÜD Rail GmbH[1], in Görlitz, Germany. Figure 8 shows pre- and post-test photographs of the pushback coupler test article and Figure 9 shows pre- and post-test photographs of the deformable anti-climber test article. For the pushback coupler test, the test article was mounted to the initially moving freight car, which impacted a fixed wall. For the deformable anti-climber test, the test article was mounted to the fixed wall and impacted by the freight car. 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.

[1] TÜV SÜD Group is a commercial consulting and testing company which owns and operates a railroad test facility in Görlitz, Germany.

Figure 8. A photograph of the push-back coupler test article mounted on the impact car and the push-back coupler deformation tube after impact

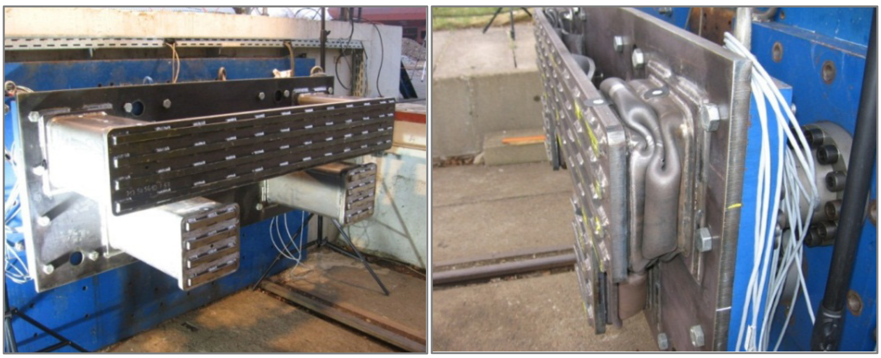

Figure 9. Photographs of the deformable anti-climber test article before and after impact

Work is ongoing to retrofit pushback couplers and deformable anti-climbers onto conventional locomotives and conducting full-scale dynamic impact tests of colliding cars and colliding trains. Service tests to measure the impact speed at which the pushback coupler just triggers are planned, as well as higher-speed impact tests to measure effectiveness of the components with conventional locomotives, cab cars, and freight cars. These tests are planned for the summer of 2015 at the Transportation Technology Center (TTC) in Pueblo, Colorado[2].

The overridden locomotive involved in the Red Oak accident was compliant with the latest FRA regulations and AAR standards. A push-back coupler and deformable anti-climber on the locomotive might have mitigated the severity of the collision. When the current regulations and standards were adopted, the technology for push-back couplers and deformable anti-climbers was not sufficiently mature to allow their introduction into service. This research effort has endeavored to develop this technology further and provide the technical basis for including push-back couplers and deformable anti-climbers in future specifications.

4.2 LNG

Currently, there is much interest in the U.S. in using (LNG) as a locomotive fuel. The relative cost of LNG is about 1/6 the cost of diesel, for the same amount of

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[2] TTC is a U.S. DOT owned facility that is managed by FRA and operated by Transportation Technology Center Incorporated (TTCI), a subsidiary of AAR.

latent energy. LNG is a pressurized cryogenic fluid, and for the same locomotive travel distance about twice the volume of LNG is needed as diesel fuel. There is not sufficient space available on a locomotive platform to double the capacity of the fuel tank. In order to maintain the same travel range as a diesel-fueled locomotive, a fuel tender is needed for an LNG-fueled locomotive. There are many safety considerations in implementing LNG as a railroad industry-wide locomotive fuel. One consideration is the crashworthiness of the locomotive and tender.

LNG fuel tenders are being developed in phases. Legacy fuel tenders, from research conducted by Union Pacific and Burlington Northern Railroads in the 1990s, are to be used to develop reliable engine and tender fuel handling components. These legacy fuel tender designs are based on traditional pressurized tank car designs. A single tender is intended to supply two locomotives in a locomotive-tender-locomotive configuration. Simultaneously, the Association of American Railroads is developing standards for production LNG fuel tenders.

FRA is sharing research results with the industry working group developing crashworthiness specifications for production tenders, the AAR Locomotive Committee/LNG Technical Advisory Group (LNG TAG). FRA is working with the industry to define the collision scenarios of concern, evaluate the crashworthiness performance of legacy LNG fuel tenders, evaluate the crashworthiness performance of alternative-design LNG fuel tenders, and compare legacy and alternative-design LNG tender crashworthiness performance. The LNG tender crashworthiness standards are expected to incorporate cost-effective and practical research results and also reflect industry experience.

Five collision scenarios have been accepted by the LNG TAG, which are listed in Table 1. These scenarios include a train-to-train collision, a grade-crossing impact, rollover, shell impact, and head impact. The train-to-train scenario results in a high compressive load being applied to the tender. The grade-crossing and rollover scenarios result in high loads being applied to the valves and plumbing. The shell and head scenarios results in concentrated loads being applied to the side of the tank and to the end of the tank. These scenarios were accepted by the LNG Tag as bounding the range of impacts that the LNG tender may experience in service.

Table 1. Candidate Collision Scenarios for LNG Fuel Tender Crashworthiness

#	Scenario	Mode	Threat to Tender
1	Head-on collision between LNG locomotive-led freight train and diesel locomotive-led freight train	Compressive impact load on tender underframe	LNG tender underframe cripples
2	Collision of highway vehicle into LNG tender at grade-crossing	Blunt impact of LNG tender side valves and fittings	Valve and fitting failure
3	Derailment and rollover of LNG tender	Blunt impact of LNG tender roof valves and fittings	Valve and fitting failure
4	Derailment and rail car impact into LNG tender tank shell	Blunt impact to LNG tender tank shell	Loss of LNG tank integrity
5	Derailment and rail car impact into LNG tender tank head	Blunt impact to LNG tender tank head	Loss of LNG tank integrity

Preliminary analyses of the legacy tenders have been conducted for FRA and shared with the LNG TAG. Underframe strength and interaction of the tender with the locomotives has been identified as a particular concern. Work is ongoing to develop and evaluate alternative crashworthiness strategies for LNG tenders and locomotives. Results from the locomotive CEM research are being considered for adaptation to LNG fuel tenders, as are results from hazmat tank car integrity research (26).

5 SUMMARY

The continued occurrence of train accidents has motivated the government and industry to strive to improve locomotive crashworthiness. FRA has been conducting research on locomotive crashworthiness continuously since the early 1990s. This research is coordinated with research on passenger train crashworthiness and with research on hazmat tank car integrity. The research results are applied to help develop federal regulations and industry standards, which result in equipment with improved-crashworthiness being put into service. The accidents, research, standards, and incrementally improved equipment constitute steps in an evolutionary cycle, in which continuous research supports continuously improving standards and safer designs.

Current practice for locomotive crashworthiness includes federal regulations and industry standards. The federal regulations for locomotive crashworthiness are performance-based and include impact scenarios that are intended to bound the range of potential accidents and incidents. Compliance can typically be demonstrated with computer simulations, non-destructive car-level tests, and destructive component tests. The industry standards are design-based and include static load requirements that are intended to result in particular design features that are effective over the range of expected accident and incident conditions. Compliance can typically be demonstrated with classical manual engineering calculations and non-destructive tests. The design-based industry standards are intended to provide the same level of crashworthiness for a traditionally-designed North American locomotive as the performance-based federal regulations.

Recent accidents show the strengths and weaknesses of current locomotive crashworthiness design practice in the U.S. On January 6, 2012 in Valparaiso, Indiana, one train rear travelling at 43 mph rear ended a second train. A third train, travelling at 50 mph, collided with the derailed locomotives of the first train. Although injured, all train crew members survived. On April 17, 2011 a freight train travelling at 23 mph collided with standing maintenance of way equipment. All of the locomotive crew members were fatally injured when the locomotive was overridden by the equipment.

Current research on locomotive crashworthiness has focused on inhibiting override and managing the load path between the locomotive in the event of collision with other rail equipment. Crash energy management features, including pushback couplers and deformable anti-climbers, have been developed which provide crashworthiness compatibility with passenger-carrying cab cars, conventional locomotives, and freight cars. Deformable anti-climbers and pushback couplers have been successfully component tested. Fullscale car-to-car and train-to-train tests are planned of modified locomotives.

The latest in crashworthiness technology is being applied to assure that LNG fuel tenders and LNG-fueled locomotives are at least as crashworthy as diesel-fueled locomotives. FRA is working with the industry to define the collision scenarios of concern, evaluate the crashworthiness performance of legacy LNG fuel tenders, evaluate the crashworthiness performance of alternative-design LNG fuel tenders, and compare legacy and alternative-design LNG tender crashworthiness performance. The LNG tender crashworthiness standards are expected to incorporate cost-effective and practical research results and also reflect industry experience.

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