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RAKING IMPACT OF A DIESEL MULTIPLE UNIT FUEL TANK: RESULTS OF TEST NO. 2 AND ANALYSIS

Karina Jacobsen
Michael Carolan
Volpe National Transportation Systems Center
United States Department of Transportation
Cambridge, Massachusetts, USA

ABSTRACT

The Federal Railroad Administration (FRA) sponsors research on safety topics to address and to improve safety regulations and standards. This paper is part of a series of papers that describe the testing and analysis used to evaluate passenger locomotive fuel tank integrity. Fuel tank integrity federal regulations, as well as industry standards, currently exist in the form of a series of static load conditions. The static load conditions are a set of prescribed loads on all passenger fuel tanks, which set a minimum level of protection against impacts that might puncture the tank and cause the release of diesel fuel. If diesel fuel is ignited in an impact incident, collision or derailment, the crew and passengers may be at risk. In the current research program a series of dynamic impact tests and quasi-static tests were conducted that measure the forces required to deform a fuel tank and investigate the types of loading conditions experienced by fuel tanks.

The objective of the testing program is to establish the baseline puncture resistance of current locomotive fuel tanks under dynamic impact conditions and to develop performance requirements for an appropriate level of puncture resistance in alternative fuel tank designs, such as Diesel Multiple Unit (DMU) fuel tanks. The tests were divided into two loading scenarios identified from accidents: blunt impact and raking impact.

In the most recent phase of testing, DMU fuel tanks were tested in a test setup that quasi-statically loaded the side and bottom of the fuel tanks. Conducted in December 2018 and November 2019, these tests were designed to simulate a raking impact scenario of a fuel tank. The Transportation Technology Center Inc. (TTCI), with support from the Volpe Center designed a test setup using a fuel tank mounted to a boxcar placed within the "squeeze frame". An indenter, shaped like a broken rail, is fixed to the ground and the fuel tank is slowly pushed into the indenter using a series of hydraulic rams. Load cells and string potentiometers are used to measure the force/displacement. Cameras capture the deformation profile of the fuel tank. The Volpe Center develops and performs finite element analysis to evaluate the loading scenario prior to testing.

In this paper, the results of the second raking test are described. A companion paper, previously published, presented the results of the first raking test. During the second raking test, the indenter was aligned beneath the bottom surface of fuel tank. The fuel tank, mounted to a boxcar, was pushed toward the indenter. Due to the downward sloping surface of the fuel tank, the indenter, maintained at a constant vertical height, began to contact the fuel tank bottom surface and push into the surface as it was advanced a total of 42 inches. The results of pre-test analyses for the second raking impact test are presented to highlight the critical position on the impacted fuel tank. The analysis gives an estimate of the force required to puncture the fuel tank as well as the resultant tear of the fuel tank.

These results highlight the detailed differences of quasi-static versus dynamic loading of fuel tanks, which supports defining trade-offs between specifying static load requirements versus scenario-defined performance based standards. The development of and results from the finite element model show the uses and limitations of the finite element models in understanding material failure. The results may be used by industry to better understand how design choices can influence fuel tank integrity against impacts and also guide standard

development of less prescriptive load requirements that still uphold equivalent safety requirements as the existing standards.

INTRODUCTION

In support of the regulatory process the FRA's Train Occupant Protection Research Program focuses on evaluating the safety performance of existing railroad equipment as well as supporting the advancement of new rail technologies and improved designs. Current research is focused on assessing fuel tank crashworthiness during dynamic impacts in order to assess the applicability of current fuel tank standards on the growing number of alternative passenger equipment fuel tank designs, like those on DMUs. DMUs are unique passenger rail cars from a regulatory perspective. They are classified in the current regulations as "locomotives" [1] though they weigh significantly less, contain more occupants, and carry a smaller fuel tank than vehicles fitting the traditional concept of a locomotive.

A research program has been ongoing to assess conventional passenger locomotive fuel tanks and alternatively-designed passenger equipment fuel tanks. The research program follows the methodology illustrated in Figure 1. Field investigations conducted by FRA provide value data on the behavior on existing equipment in collisions, derailments and general operation. The results show what equipment is performing sufficiently, according to the regulations and standards it's designed to, and highlight areas of improvement. Conducting research through analysis and testing allows us to measure the forces imparted on fuel tanks in impacts and determine the response of equipment under different loading conditions. The research results are used to help support regulatory and standard development.

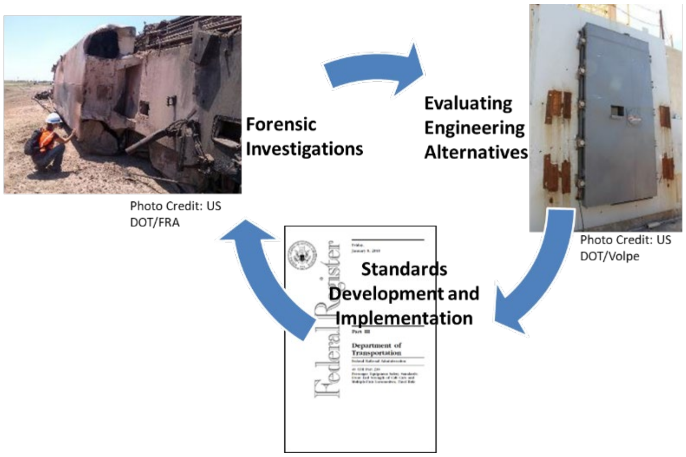


Photo Credit: US DOT/FRA

Photo Credit: US DOT/Volpe

Figure 1. Flow Diagram of Crashworthiness Research Methodology

As part of the FRA research effort, a survey was conducted of accidents and derailments in the U.S. over the last two decades in which fuel tanks were punctured [2]. The information on incidents was found using a combination of the FRA accident database and in-person field investigations conducted by FRA inspectors and support staff from the Volpe Center. The surveys consisted of freight and passenger trains involved in accidents or derailments during which one or more fuel tanks ruptured; some sources surveyed contained limited detailed information. Two key findings should be noted from the results of this study. First, a fuel tank rupture during a train collision or derailment may result in a fire, which presents additional threats to the survivability of passengers and crew as they egress from the collision wreckage. The presence of occupants onboard DMUs increases the risks associated with a diesel spill, fire, and associated injuries and/or fatalities. The second key finding is that each fuel tank impact scenario can be categorized by its resultant loading type, of which there are two general loading conditions leading to punctures: blunt impacts and raking impacts.

The schematics in Figure 2 illustrate two idealized loading scenarios identified in this research that can penetrate an exposed surface of a fuel tank. In this research a "blunt" impact is characterized by a rigid object aligned relative to a fuel tank such that it imparts a primarily perpendicular force to the fuel tank surface. A "raking" impact is characterized by a rigid object initially aligned at a primarily tangential force applying a tearing load upon the tank. Blunt and raking loads are both able to act upon the bottom or sides of the fuel tank.

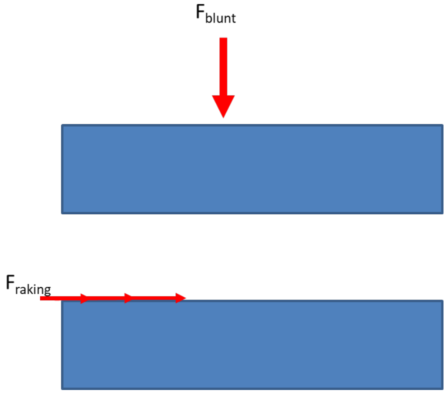


Figure 2. Force Diagrams of Fuel Tank Loading Types

This paper describes the efforts conducted to launch the evaluation of a raking impact scenario. The recent survey of fuel tank puncture incidents included multiple example incidents highlighting the possibility of a raking impact occurring. One example involved two freight trains colliding at a switch in Newark, New Jersey on April 28, 2012. A schematic of the impact is illustrated in Figure 3. In this incident two locomotives impacted the side of another train at a switch. Through the sequence of events a doortrack of the trailing freight car was dragged along the side of the lead locomotive fuel tank [3]. Since both trains were moving in the same direction, as the trains collided, the two coupled locomotives derailed but scraped along the side of the main line train. The doortrack of the fifth car impacted the end plate of the locomotive, piercing directly into the fuel tank and through nearly the full length of the tank. The resulting damage to the fuel tank is shown in Figure 4.

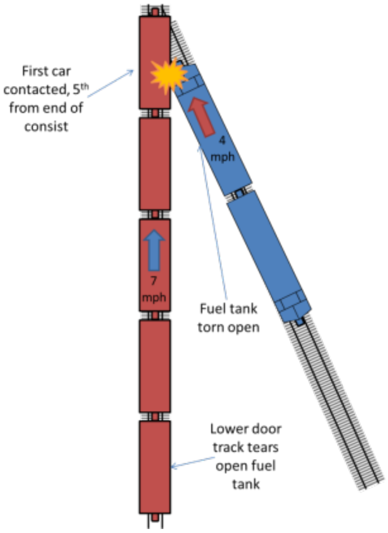


Figure 3. Schematic of Raking Impact in Oak Island Yard in Newark, NJ

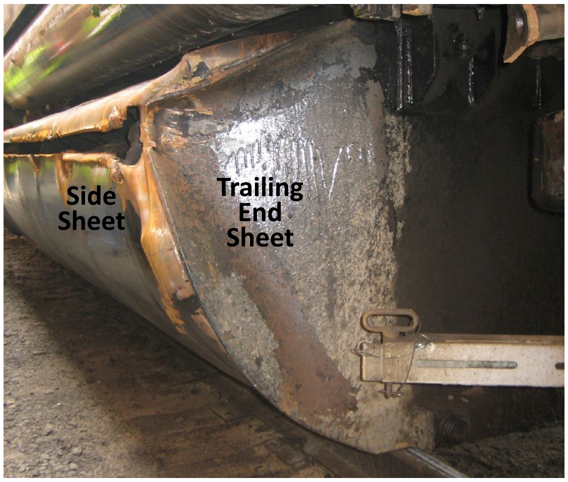


Figure 4. Damage to Trailing Locomotive Fuel Tank

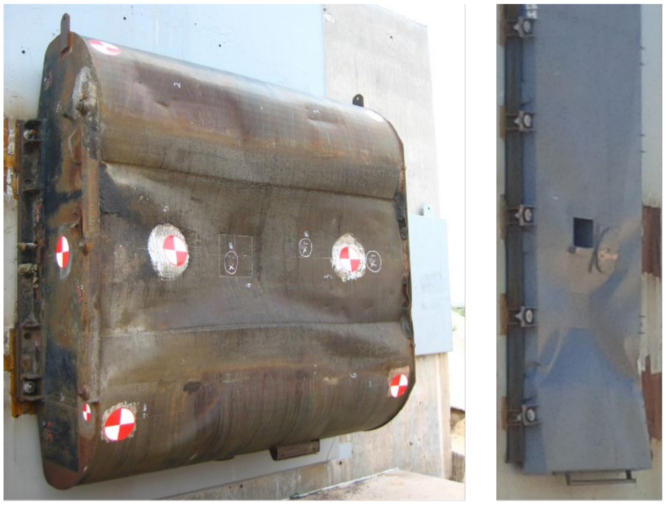
A second example incident occurred in Goodwell, Oklahoma on June 24, 2012, in which two freight trains collided head on at nearly 100 mph closing speed [4]. Three of five locomotive fuel tanks were puncture with both blunt and raking impacts. Figure 5 shows a post-collision photo of a rolled over locomotive. It shows a variety of striations as well as a deformed bottom surface. Some of the plastically deformed sections could be due to impacts though some of the plastically deformation is likely a result of sustained extreme temperatures from the diesel fire that burned for nearly 24 hours. Figure 6 shows a close up photo to one section of the fuel tank with a distinct puncture mark about 2 feet long [3]. The bottom of the fuel tank includes striations that run the full length of the fuel tank and suggest the tank was moving along the ground for a length of time. At a certain point the fuel tank impacted a rigid object or structure that cut into the tank. The detail of this fuel tank puncture measured two distinct 1-foot long tears. A discontinuity in the 2-foot tear occurred at the location of a lateral baffle. The baffle is attached to the inner surface of the fuel tank, thereby stiffening the bottom surface at the location.

Figure 5. UP4855 Locomotive, Rolled Over with Bottom of Fuel Tank Exposed

Figure 6. Close-up of UP4855 Fuel Tank Puncture

As part of the FRA research into fuel tanks, a series of full-scale tests have been conducted to evaluate fuel tanks under the identified loading scenarios: a blunt and raking impact. Four dynamic blunt impact tests were conducted on a series of four different fuel tanks: three conventional passenger locomotive fuel tanks and a DMU fuel tank. The objectives of these tests were to measure the performance of fuel tanks under a dynamic blunt impact [5][6][7][8][9].

In the blunt impact tests, the details of the fuel tank internal baffle construction proved to contribute to the progression of each tank's response to the load. Results of one blunt impact test, a conventional fuel tank from an F40 locomotive (#234), featured a very low initial force after impact, attributed to the gap between the interior of the bottom of the tank and the lateral baffles followed by climb up to the peak force. Contrastingly, the DMU fuel tank features baffles that are spot-welded to the bottom sheet. The DMU fuel tank experienced a high initial force, while the conventional tank does not experience a significant increase in stiffness until the bottom sheet closes the gap to the baffles. Both tanks experienced buckling of their respective baffles, which resulted in a temporary decrease in force. The deformed shapes of the F40 fuel tank and the DMU fuel tank are shown in Figure 7. Because it was so much stiffer, the DMU fuel tank experienced much less deformation compared to the conventional fuel tank. However, because the DMU fuel tank had a smaller overall height than the conventional fuel tank, the maximum indentation experienced by the DMU tank was a much larger reduction in height as a percentage of the initial height of the tank.



Post-test Photograph
Tank 234

Post-test Photograph
DMU Tank

Figure 7. Deformed Shapes of Tank 234 (Left) and DMU Fuel Tank (Right)

TEST – RAKING SCENARIO

On December 18, 2018, a preliminary test designed to simulate a raking impact was conducted on the DMU fuel tank previously-tested in the blunt impact test. The indenter was positioned between the rails at a height such that the top front edge had two inches of overlap with the front end plate of the fuel tank. The DMU fuel tank was suspended beneath a boxcar, which was placed into a "squeeze fixture" at TTCI. The boxcar was advanced toward the indenter using hydraulic actuators. The indenter top edge slid past the fuel tank's end plate edge and made contact with the fuel tank bottom surface. The test successfully measured the forces applied to the boxcar, and reacted between the tank and the indenter. On November 13, 2019, a second raking test was conducted on a new DMU fuel tank in a second location along the bottom of the fuel tank. The indenter was positioned between the rail and in the same orientation as the preliminary test but at a lower height and different lateral position relative to the fuel tank. The subsequent sections of this paper describe the test setup, pre-test modeling and test and model results of the second raking test.

Objective

The key objective of the raking testing of fuel tanks was to examine the gross response of the fuel tanks to a given impact type. The raking test was designed to characterize each test specimen's deformation behavior when scraped along the bottom sheet, both with and without first engaging the end sheet. The overall approach to characterizing the deformation behavior includes:

1. Develop an analytical model of the fuel tank specimen based upon known design details.
    - Use the analytical model to plan for tests.
    - Estimate possible fuel tank behavior under test impact conditions.
2. Design test setup to apply desired load to fuel tank.
    - Develop test setup for achieving desired load path and load application on fuel tank.
    - Fabricate indenter.
    - Develop and fabricate test fixture for indenter.
    - Develop mounting scheme for fuel tank and modify boxcar.
    - Perform pre-test checks on test setup to validate desired load path.
3. Apply a scraping load to the bottom surface of a fuel tank specimen.
    - Measure the force-deflection behavior of the tank with specified instrumentation.
    - Record mode of deformation with conventional video cameras.
    - Record permanent deformation by surface light detection and ranging (LIDAR) scans.
4. Conduct post-test examination of the tank.
    - Characterize structural deformation of tank exterior and interior.
5. Validate the model.
    - Compare test results to model predictions.
    - Revise model as necessary.

The outcome of this process can be used to make a comparison between fuel tanks of different designs, with analysis techniques being used to provide additional information on the fuel tank behavior. Modeling can also be used to simulate additional impact conditions beyond what was tested, providing additional points of comparison between different designs.

Test Development and Setup

The raking test scenario was designed to simulate a DMU fuel tank loaded tangentially along a surface, i.e., end plate, bottom, or side of tank, by a relatively rigid object. Using computer analysis to assess some general object shapes and sizes, an indenter was chosen to approximate the dimensions of a section of broken rail. In order to puncture the fuel tank in a raking collision it was determined that the object must be much smaller and narrower than the 12 inch square indenter head used in the blunt impacts.

As described in detail in a previous paper, a raking test setup was developed and tested on December 18, 2018 [10]. A fuel tank mounted to a rail vehicle within the "squeeze frame" is advanced along the rails toward an indenter mounted to the ground, with a load cell positioned behind it. The rail vehicle is advanced by a hydraulic cylinder located within the squeeze frame, simulating a slow motion raking incident as indenter "rakes" along the bottom of the fuel tank moving over it. The indenter base is constructed prior to the test to be rigid and to position the indenter relative to the fuel tank at the desired height and lateral location. The reaction load is measured by a load cell supporting the rear of the indenter.

In the preliminary raking test [10], the indenter was positioned so that there are two inches of vertical contact between the front face of the indenter and the end plate of the fuel tank. For the second raking test the indenter base plate was modified and the indenter position shifted. The base plate was lowered to position the indenter just below the end plate bottom edge and moved laterally to position the indenter more toward the center of the tank. The setup in the first test (Figure 8) was meant to represent a raking impact in which the indenter engaged the end plate of the tank, while the setup in the second test (Figure 9) was meant to represent a raking impact in which the indenter bypassed the end plate of the tank and made contact directly with the bottom of the tank. Note that the photograph of the second test setup was taken before the load cell was installed between the indenter and the base plate, but a similar load cell configuration was used as in the first test.

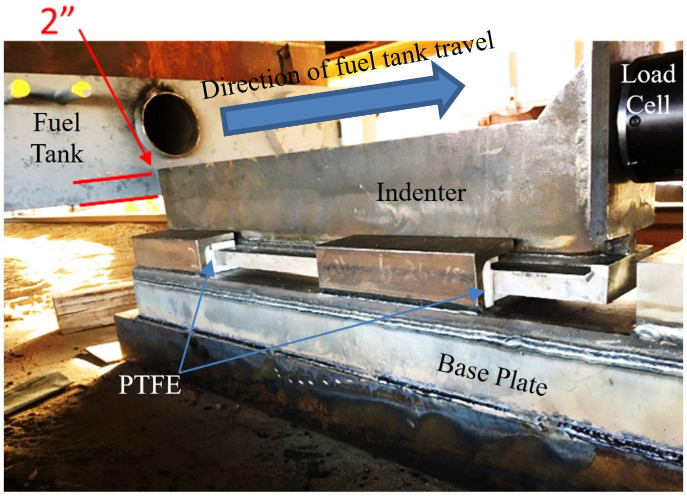


Figure 8. Fuel Tank and Indenter Setup for First Raking Test

Figure 9. Fuel Tank and Indenter Setup for Second Raking Test

INSTRUMENTATION

The objectives of the test were to characterize the fuel tank deformation behavior and assess the details of the test setup in creating a controllable dynamic impact condition. The primary measurement made during this test was the force-versus-displacement behavior of the fuel tank raking along the indenter, which equates to measuring the load reacted and the advancement of the boxcar into the indenter. Table 1 lists instrumentation used in the second quasi-static raking test of DMU fuel tank.

Table 1. Instrumentation for Quasi-static Raking Test of DMU Tanks

Type of Instrumentation	Channel Count
String Potentiometers	6
Load Cells	2
Displacement from Hydraulic Cylinders	2
Pressure from Hydraulic Cylinders	2
Laser Displacement	1
Total Data Channels	**14**
Digital Video	3 Cameras

String potentiometers and load cells were mounted on the boxcar and test fixture arrangement as illustrated in the schematic in Figure 10. The red lines indicate the positions of the string potentiometers. These measure the longitudinal displacement of the boxcar on left and right sides and a laser sensor (not shown) measures the vertical displacement of the boxcar on one side. The hydraulic ram on the right side of the schematic advances the boxcar longitudinally into the indenter. The reaction load is measured with the load cell behind (to the left) of the indenter.

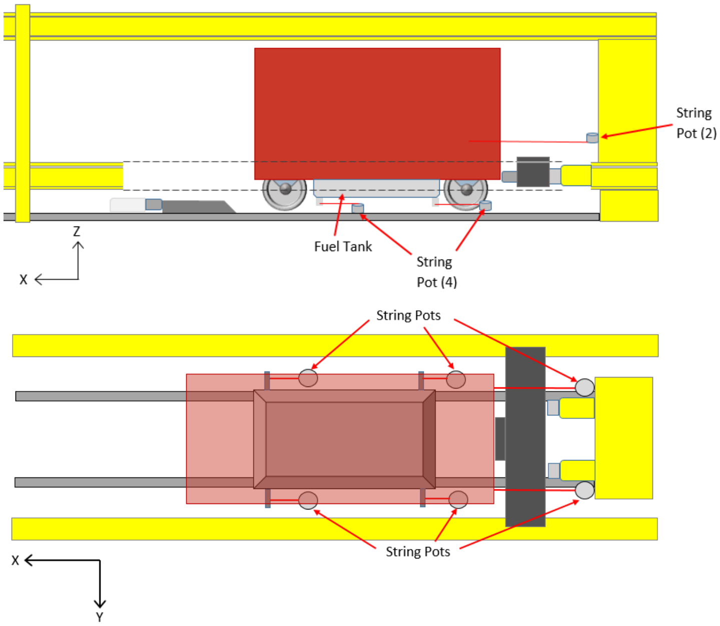


Figure 10. Schematic Showing Side and Plan Views of Test Fixture with String Potentiometers Indicated

The top photograph of Figure 11 shows the load cell positioned between the sled assembly and the boxcar draw bar, measuring the load applied. The bottom view of photograph of Figure 11 shows the load cell positioned between the back of the indenter and the backing plate, measuring the reaction load. Note that in the bottom view the instrumentation is covered by plastic to protect it from moisture prior to the test.

Figure 11. Load Cells Measuring the Applied Load (Top) and Reacted Load (Bottom)

Three digital cameras were used to record the test. One was placed beneath the bottom of the tank just forward of the indenter to capture the contact zone between the indenter and the tank. The second camera was located to the side of the indenter with an oblique view of the indenter, front edge of the tank and bottom of the tank.

TEST SPECIMEN

A set of new DMU tanks were purchased by FRA as part of the passenger locomotive fuel tank research project. The fuel tanks are a design that is currently in operation in the U.S. The DMU fuel tanks do not meet FRA's existing requirements for locomotive fuel tanks (49 CFR 238, Appendix D) and are subject to operation under a waiver granted by FRA's Office of Safety. The DMU fuel tanks have since been redesigned by the manufacturer to include a shield as part of the integrated fuel tank design and no longer require a waiver when installed in this form.

Figure 12 shows a side (left) and bottom (right) view of the DMU fuel tank used in the testing program. These images are from the finite element model developed of the DMU fuel tank prior to the test. The fuel tank is relatively shallow in comparison to a conventional locomotive tank and its shorter bottom surface dimension spans almost the full width of a DMU railcar. In the bottom view, the longitudinal and lateral dashed lines indicate the locations of the internal baffles. The bottom surface of the fuel tank is non-planar as indicated by the diagonal lines on the bottom view. The bottom of the fuel tank slants slightly downward toward the circular drain cover.

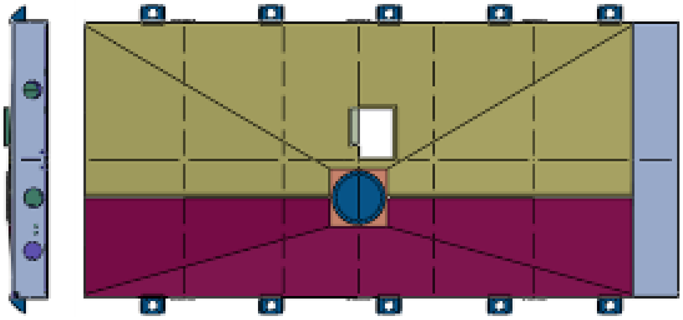


Figure 12. Side (Left) and Bottom (Right) Views of DMU Fuel Tank from the Finite Element Model

TEST RESULTS

The second raking impact test was conducted on November 13, 2019, at Transportation Technology Center (TTC). The test setup was similar to the first test, but with the indenter positioned at a lower height such that the top edge of the indenter would bypass the end plate of the fuel tank and make direct contact with the bottom sheet. The indenter was positioned 17 inches past the end plate, such that, as the fuel tank advanced over the indenter, the top indenter edge would begin to make contact with the bottom fuel tank sheet, which slopes downward toward the center of the fuel tank.

As the fuel tank advanced the indenter scraped into the paint as can be seen in the post-test photo in Figure 13. The indenter edge was initially located on the right side of this photo, where the scrape mark begins. At about 21 inches of displacement the indenter punctured the fuel tank. The indenter then continued to scrape the bottom of the fuel tank for an additional 22 inches and punctured into the tank a second time at about 44 inches of total displacement. Figure 14 and Figure 15 show close ups of the two punctures. Tearing in the fuel tank was initiated at the locations of the internal, lateral baffles. The now-exposed baffle is visible in the close-up of the first puncture in Figure 14. The puncture measured about an inch long and ¾ inch wide. Like the preliminary raking test, the fuel tank deformation was highly localized. The second puncture, shown close-up in Figure 15 measured about ¾ inch long by ¾ inch wide.

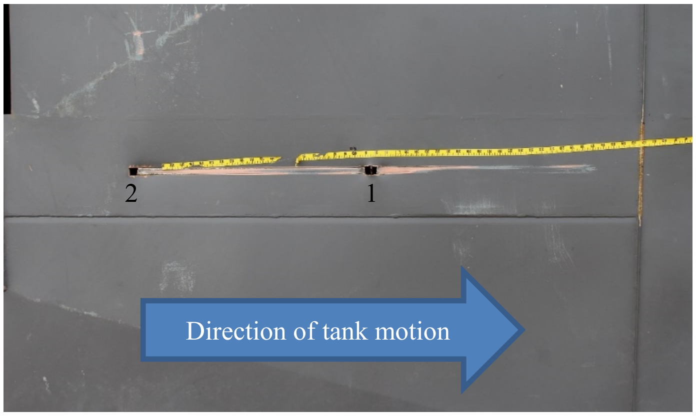


Figure 13. Scrape Marks and Punctures in Test 2 Fuel Tank

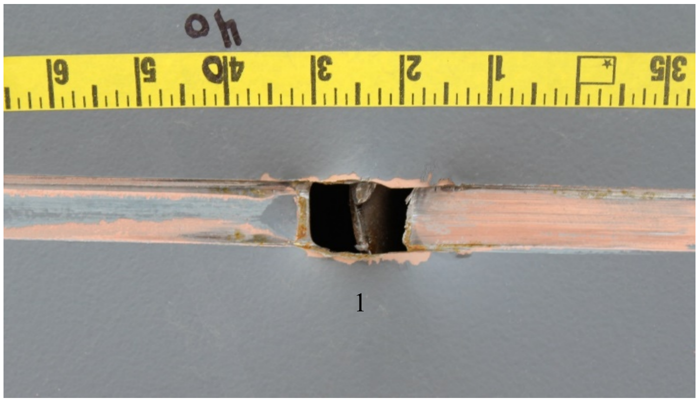


Figure 14. First Tear in Test 2 Fuel Tank

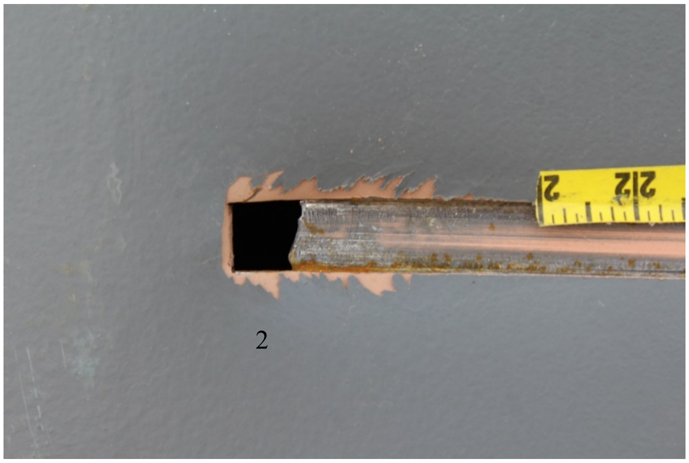


Figure 15. Second Tear in Test 2 Fuel Tank

TEST MEASUREMENTS

Force was measured at the load end of the boxcar, and at the point of load reaction at the indenter. The test began without the indenter in full contact with its load cell. As the raking continued, the fuel tank pushed the indenter up to the load cell which then began to record a force output. This occurred during the second push with the hydraulic cylinders at 16.8 inches of displacement. As such the indenter load cell does not match the reading of the boxcar load cell until 16.8 inches of displacement, at which point the indenter load cell closely matches the force-displacement history of the boxcar load cell. The force versus displacement measurements are shown in Figure 16. The maximum force measured during this test was approximately 21 kips at about distance of 20.3 inches of displacement. During the highest observed forces of the test, the indenter load cell measured a slightly higher force than the boxcar load cell. This result was unexpected, as the indenter load cell was reacting the force applied through the boxcar load cell. As such, the force measured from the indenter load cell was anticipated to be equal to or lower than the force measured at the boxcar load cell due to frictional forces and other minor losses in the load path between the applied load at the boxcar load cell and the reacted load at load cell supporting the indenter.

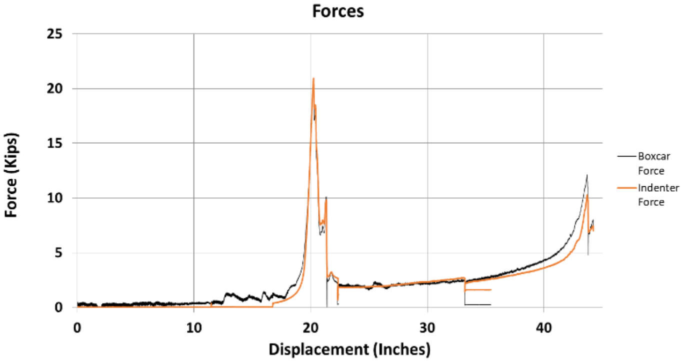


Figure 16. Test 2 Combined Force Measurements

Displacement of the boxcar and the fuel tank were measured relative to the ground. These measurements show similar displacement histories. Each measurement shows four separate periods of movement during the test of approximately 11 inches each, with a stationary period in-between. This represents the four strokes of the squeeze fixture's hydraulic cylinders with periods in-between to restrain the boxcar and install extenders. The displacement measurements are shown below in Figure 17.

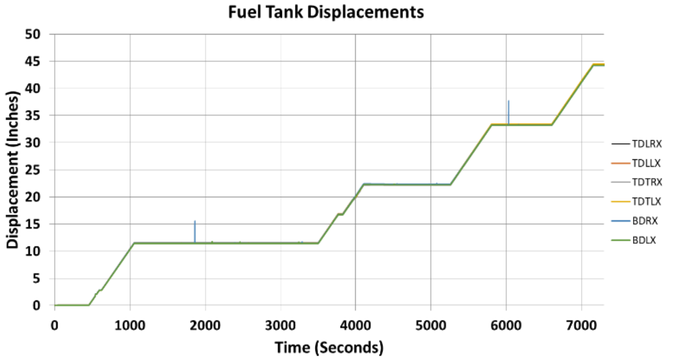


Figure 17. Test 2 Combined Displacement Measurements

MODELING COMPARISONS

Pre-test finite element analysis (FEA) was performed to help establish the initial position of the indenter and the fuel tank. The starting point for pre-test-2 model was the post-test-1 model [10], which was developed in Abaqus/CAE software. The simulations were executed in Abaqus/Explicit software [11]. The pre-test-2 model continued the approach of using a refined mesh, a simplified representation of the mounting hardware, and a combination of rigid and deformable areas on the fuel tank to reduce simulation runtime.

The pre-test 2 model was used to examine several different lateral positions of the indenter. These positions were intended to explore whether the tank is more vulnerable to tearing from a raking impact to different areas of the bottom of the tank. Test 2 targeted the same end of the DMU fuel tank as had been raked in the first test. Three potential locations were examined using the pre-test 2 model:

- Indenter shifted laterally in the +X direction, adjacent to the tank's longitudinal baffle;
- Indenter shifted laterally in the +X direction, halfway between the longitudinal baffle and Test 1 position, and;
- Indenter shifted laterally in the –X direction, halfway between tank's edge and longitudinal weld seam position

The three lateral positions of the indenter are shown in Figure 18.

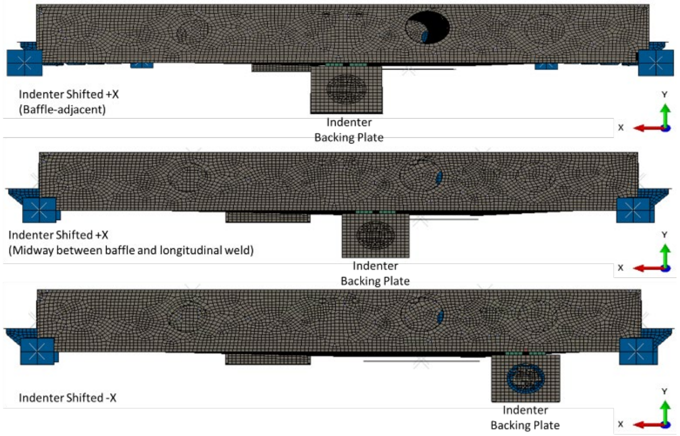


Figure 18. Three Lateral Positions of Indenter Examined in Pre-test-2 Model

For any of the three locations chosen, the vertical overlap between the top of the indenter and the bottom of the fuel tank would increase as the displacement of the fuel tank increased, due to the tank's sloped bottom sheet. The indenter's height under the tank was limited to prevent it from contacting the end sheet of the tank, which extended below the tank's bottom sheet.

Based on the desired outcome of tearing the tank, the limitations of the clearances and the overall test setup, and the anticipated forces involved, the indenter was positioned midway between the baffle and the longitudinal weld for raking test 2 (shown in the middle image in Figure 18).

GEOMETRY, MATERIALS, BOUNDARY CONDITIONS, AND INITIAL CONDITIONS

The geometry of the DMU fuel tank used in the pre-test-2 FE model is based on the geometry used in the post-test-1 FE model. The most significant change to the geometry is the area of refined mesh in the pre-test-2 model. Since the position of the Indenter has been shifted laterally, the refined patch of elements in the DMU fuel tank has also been shifted laterally to place it in the path of the indenter. The geometry of the pre-test-2 FE model is shown in Figure 19. Note that the bottom of this figure shows the model viewed from underneath, and the top of this figure shows the model viewed from above.

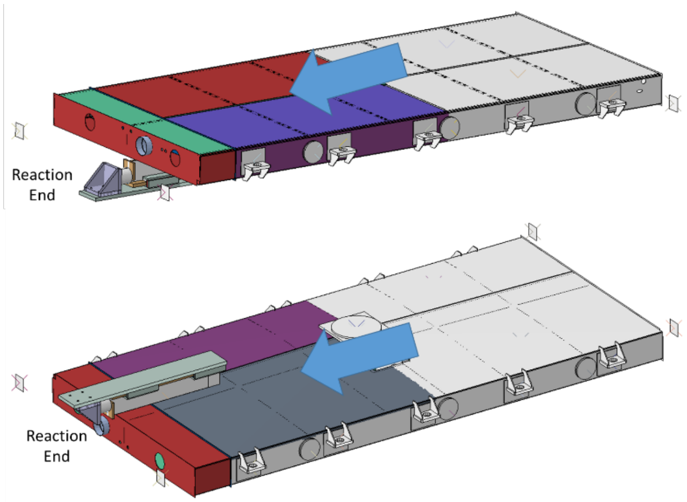


Figure 19. Pre-test-2 FE model Setup, Indenter Shifted between Test 1 Position and Longitudinal Baffle

Similar to the post-test-1 FE model, the pre-test-2 FE model used a refined mesh of elements (approximately 1 mm, or 0.04 inches) in the path of the indenter. This zone of refined elements is shown in Figure 20. Note that the tank and indenter are inverted in this image.

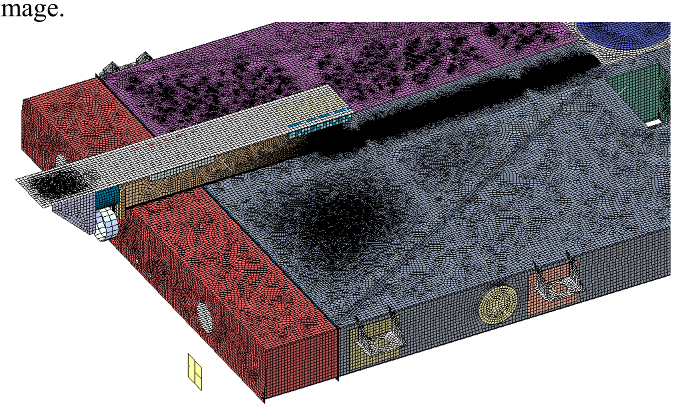


Figure 20. Refined Mesh in Path of Indenter, Pre-test-2 FE Model

The pre-test-2 DMU fuel tank was meshed using a combination of deformable and rigid shell elements to reduce the model's runtime. The indenter was not observed to have any significant permanent deformation following the test, so the post-test-1 FE model used a rigid indenter. The pre-test-2 FE model used the same material behaviors as the post-test-1 FE model [10]. The mesh techniques used in the post-test-1 FE model are summarized in Table 2.

Table 2. Summary of Mesh in Pre-test-2 FE Models

Part Name	Element Type	Number of Elements
Deformable Backing Plate	Reduced Integration Triangular Shell (S3R)	34
	Reduced Integration Quadrilateral Shell (S4R)	957
Deformable Base Plate	Reduced Integration Triangular Shell (S3R)	30
	Reduced Integration Quadrilateral Shell (S4R)	2,693
Deformable PTFE Shims	Reduced Integration Hexahedral Continuum (C3D8R)	200
Indenter	Reduced Integration Hexahedral Continuum (C3D8R)	178,228
	Reduced Integration Quadrilateral Shell (S4R)	3,999
DMU Fuel Tank	Reduced Integration Quadrilateral Shell (S4R)	235,206
	Reduced Integration Triangular Shell (S3R)	6,263
	Rigid Triangle (R3D3)	154
	Rigid Quadrilateral (R3D4)	36,939
Rigid Plate	Rigid Quadrilateral (R3D4)	4
	Rigid Body Reference Node (RNODE3D)	1

The indenter geometry was modified in the pre-test-2 model to match the indenter modifications used in test 2. To prevent the indenter from contacting the endplate, the indenter height was reduced between first and second raking tests. This allowed the indenter's initial position to be further under the DMU fuel tank and reduced the likelihood that the tank's end plate would contact the back of the indenter. The indenter was initially positioned with its tip in contact with the fuel tank's bottom sheet, to maximize the available stroke of the hydraulic actuators. In the FE model, the clearance between the top of the indenter and the bottom of the end plate was chosen to be 1 mm (0.04 inches). The initial position of the indenter in the pre-test-2 FE model is shown in Figure 21.

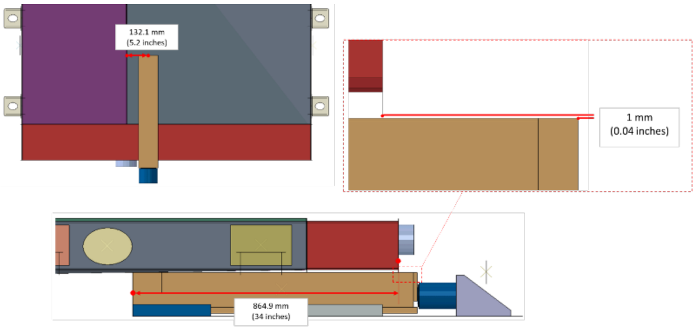


Figure 21. Initial Position of Indenter Relative to DMU Fuel Tank, Pre-test-2 Model

The pre-test-2 model featured areas of the DMU fuel tank and other parts that were modeled as rigid bodies, similar to the post-test-1 model. Areas of the fuel tank that were remote from the impact area and thus, expected to undergo limited deformation during the test, were modeled as rigid bodies. Figure 19 shows the areas of the DMU fuel tank that were modeled as rigid bodies in the pre-test-2 FE model. The multi-colored areas are modeled as deformable bodies, while the white areas are rigid bodies. The top of Figure 19 shows the pre-test-2 FE model viewed from above, while the bottom of this figure shows the model when viewed from below.

The pre-test-2 model was run in two steps. The first impact step was run for 500 ms and ran to completion. A continuation step was run for a further 250 ms of impactor travel. Variable mass scaling with a target time increment of 2 x 10^{-6} seconds was used, resulting in an additional mass of 153%. As the loading was intended to be quasi-static, this additional mass was not anticipated to have a significant effect on the overall fuel tank response to the raking impact.

The boundary conditions applied to the pre-test-2 FE model are similar to the boundary conditions used in the post-test-1 FE model. One difference is the boundary condition applied to the DMU fuel tank to move it across the indenter. Where the post-test-1 FE model used a displacement boundary condition that ramped up over a prescribed time, the pre-test-2 FE model used a constant velocity boundary condition of 1000 mm/second (39.4 inches/second). The boundary conditions in the pre-test-2 FE model are summarized in Table 3.

Table 3. Summary of Boundary Conditions in Pre-test-2 FE Model

Region	Step	Degrees-of-freedom	Value
Bottom of baseplate	All	1-3	Fixed
Rigid plates for string pots.	All	1-6	Fixed
Rigid Brackets	All	1, 2, 4, 5, 6	Fixed
Rigid Brackets	All	3	1000 mm/sec
Baseplate	All	1-3	Fixed
Load Cell	All	2	Fixed

MODEL RESULTS

Figure 22 shows a comparison between deformed shape from the pre-test-2 FE model and the test results. The model estimated a similar pattern of inelastic striation in the bottom sloped surface of the fuel tank to what occurred in the test. Two distinct locations of material failure were observed in both the model and the test results.

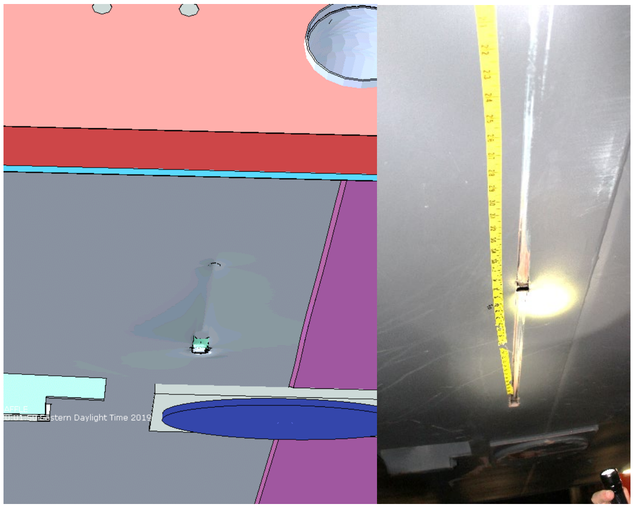


Figure 22. Comparison of Fuel Tank Deformation in Pre-test-2 FEA (left) and Test (right)

Figure 23 shows a plot of the force versus longitudinal displacement for both the test and the pre-test-2 model. This pre-test model assumed that the indenter would be positioned such that it made initial contact with the bottom of the fuel tank immediately. However, as seen in this figure, the test measurements revealed that the force did not increase immediately during the test, but rather required a significant amount of "slack" longitudinal travel to occur before the indenter load cell began to register a force.

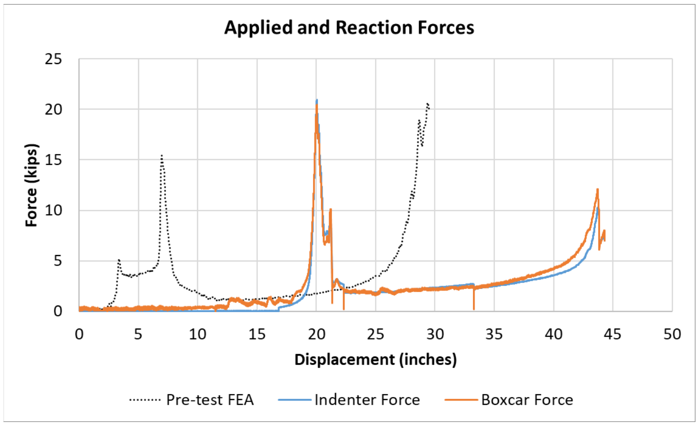


Figure 23. Comparison of Test Data and Pre-test-2 FEA (Unshifted Results)

Following the test, the pre-test-2 FEA result was shifted with respect to displacement by approximately 15 inches. This displacement corresponds to a distance midway between where the boxcar force (i.e. the live end) and the indenter force (i.e. the reaction end) experience an appreciable increase. The shifted pre-test-2 FE results are shown in Figure 24. The pre-test-2 model predicted a relatively low force of less than 2 kips until about 18 inches of shifted displacement. The force then increased to a peak of 15-20 kips and drops off within 5 inches of travel, indicating the first puncture location. The load then reached a plateau at about 2.5 kips for 20 inches of travel until a second peak occurred at about 44 inches in both the test and the shifted model.

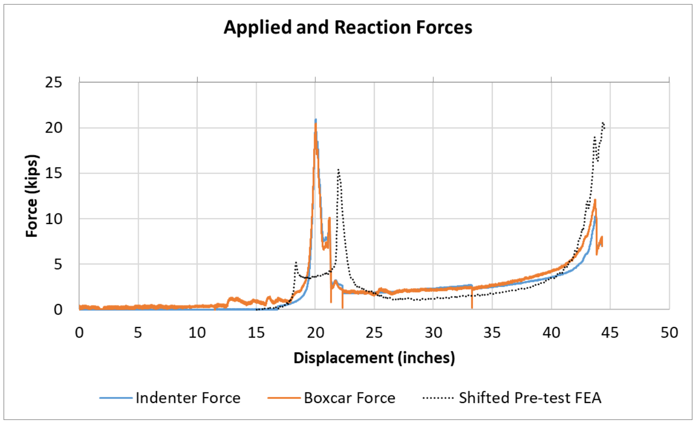


Figure 24. Comparison of Test Data and Pre-test FEA (Shifted Results)

In general, the pre-test model estimated the response of the fuel tank in raking test 2. Similar to the results of raking test 1, the force levels and the location of the peak displacements are not in perfect agreement with the test measurements. The test and model setup were found to be fairly sensitive to the initial position of the indenter relative to the tank owing to the small overlap between the top of the indenter and the bottom of the tank. Additional post-test modeling was not conducted based on the level of agreement observed between the test and the pre-test FEA.

SUMMARY AND CONCLUSIONS

Field investigation surveys have shown that locomotive fuel tanks are punctured in accidents and incidents based upon two types of loading: a blunt impact or a raking impact. To evaluate the performance of fuel tanks under these two load scenarios, two tests were developed at TTC and a series of fuel tanks tested from October 2013 and November 2019. This paper describes the results of the second quasi-static raking test performed on a DMU fuel tank.

On November 13, 2019, a second test of the idealized raking scenario was conducted. The squeeze frame test setup that successfully performed the December 18, 2018 test was used to test a raking impact along the bottom of a DMU fuel tank. The second test loaded the fuel tank such that the indenter bypassed the end plate and made direct contact with the sloped surface of bottom of the fuel tank.

The full set of tests conducted revealed the role the internal structure of a fuel tank can play in its performance. In basic fuel tank design, the purpose of baffles is to prevent sloshing of the fuel within the tank during operation. During an impact event, the baffles provide an internal structure that can influence both the global response of the tank and the localized response. The blunt impact tests, particularly with the conventional fuel tanks, showed that the location of impact was highly influenced by whether it was in-line with a baffle or striking between baffles. In the second raking test it was found that as the indenter raked along the bottom of the tank, it tore the tank only at the locations of baffles. These observations on the influence of baffles on fuel tank performance may help manufacturers design fuel tanks that can more efficiently meet performance-based strength requirements. This may be particularly helpful for alternative-style fuel tanks such those on DMUs.

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