Comparison of Methodologies for Finite Element Model Validation of Railroad Tank Car Side Impact Tests

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Background

• During derailments, railroad tank car shells can be punctured by other derailed equipment, wayside hazards, etc.
• Puncture can result in release of hazardous materials
• Federal Railroad Administration (FRA) has ongoing research program on improving puncture resistance of tank cars
  – Results can help develop alternative performance-based criteria to supplement existing design criteria
Generalized Shell Impact Scenario

- Idealized impact condition
  - Safe
  - Repeatable
  - Analyzable
  - Controllable
  - Results in failure mode(s) similar to accidents

- Provides means of evaluating puncture resistance

- Can compare various:
  - Tank designs (e.g. shell thickness)
  - Lading conditions (e.g. outage, pressure)
Evaluating Puncture Resistance

**Kinetic Energy**

Impact Speed ($v_i$)

\[ KE = \frac{1}{2} m v_i^2 \]

**Energy Absorbed**

Displacement

Force

\[ E_{abs} = \int_0^d F \, dx \]

**Energy to Maintain Tank Integrity:**

\[ KE \leq E_{abs} \]
Evaluating Puncture Resistance

- The energy absorption capacity ($E_{abs}$) of a tank car depends on:

  1. Design of the tank car
     - Quality of steel, thickness of steel, welds, supports, stiffeners, insulation, etc.

  2. Conditions at time test
     - Outage, internal/external pressure, internal/external temperature, impact velocity, mass of impactor, support conditions, etc.
Timeline of Tests

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* Test conducted in collaboration with Next Generation Rail Tank Car Project (NGRTCP)
Timeline of Tests

Test 0: April 11, 2007*
DOT105 10.0 mph

Test 2: July 11, 2007*
DOT105 15.1 mph

Test 4: December 18, 2013
DOT111 14.0 mph

Test 6: April 27, 2016
DOT105 15.2 mph

Test 8: August 1, 2018
DOT105 9.7 mph

Test 10: November 19, 2019
DOT113 16.7 mph

Test 3: May 18, 2011
DOT105+ 17.8 mph

Test 5: February 26, 2014
DOT112 14.7 mph

Test 7: September 28, 2016
DOT117 13.9 mph

Test 9: October 30, 2018
DOT111 (CPC1232) 13.9 mph

* Test conducted in collaboration with Next Generation Rail Tank Car Project (NGRTCP)

Impactor Sizes (W x H)
1. 6” x 6”
2. 12” x 12”
3. 17” x 23”

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Test Layout and Instrumentation

1. Impactor Acceleration
   - Change in Velocity
   - Displacement
2. Outage (Air) Pressure
3. String Pot 48” Offset A-End
4. String Pot 24” Offset A-End
5. String Pot 0” Offset
6. String Pot 24” Offset B-End
7. String Pot 48” Offset B-End
8. String Pot Vertical
9. String Pot Head A-End
10. String Pot Head B-End
11. String Pot Skid A-End
12. String Pot Skid B-End
Overview of FEA Model

- Tank car head, shell, and jacket elastic-plastic materials
- Tank car shell has a refined solid mesh under impactor to model crack initiation (ductile damage)
- Lading fluid-structure interaction
  - Hydraulic cavity (DOT-105)
  - Equation of state (EOS) Lagrangian brick elements (DOT-117)
- Pneumatic cavity outage able to build pressure
Potential Validation Methodologies

• Roadside Safety Verification and Validation Program (RSVVP)
  – Developed as part of National Cooperative Highway Research Program Project 22-24 (NCHRP 22-24)
  – Used for validating FE models of impact tests with roadside hardware

• Correlation and Analysis Plus (CORA)
  – Developed by Partnership for Dummy Technology and Biomechanics (PDB)
  – Used for validating FE models of anthropomorphic test devices (ATDs) in crash tests
Objective

1. Apply publicly available validation tools (CORA and RSVVP) to two recent tank car tests (DOT-105 and DOT-117)
   – Use standardized settings without modification, i.e. out-of-the-box

2. Discuss applicability of software tools to tank car side impact puncture models
Validation Metrics

- Comparing dynamic signals from impacts can be complicated
- Peak to peak comparisons or corridor comparisons can oversimplify the problem
- A single metric does not give the full picture

# Validation Metrics

<table>
<thead>
<tr>
<th></th>
<th>CORA</th>
<th>RSVVP</th>
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<tbody>
<tr>
<td>Corridor</td>
<td>Inner and Outer Corridor</td>
<td>Normalized Residual Error</td>
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<tr>
<td></td>
<td></td>
<td>Variance of Residual Error</td>
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<td>Magnitude</td>
<td>Dynamic Time Warping (DTW)</td>
<td>Root Mean Squared (Sprague-Geer)</td>
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<td>Phase</td>
<td>Time shift and Zero Normalized Cross-Correlation</td>
<td>Normalized Cross-Correlation (Sprague-Geer)</td>
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<tr>
<td>Slope</td>
<td>Downsampling and Forward Difference Approximation</td>
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<table>
<thead>
<tr>
<th>Score</th>
<th>CORA</th>
<th>RSVVP</th>
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<th>0.4</th>
<th>0.05</th>
<th>0.2</th>
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<td>0</td>
<td>0</td>
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<tr>
<td>Fail</td>
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<td>0.4</td>
<td>0.05</td>
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# DOT-105 CORA and RSVVP Scores

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<tbody>
<tr>
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<td>Phase</td>
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<td>Impactor Change in Velocity</td>
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<td>Impactor Displacement</td>
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<td>0.68</td>
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<tr>
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<td>String Pot 24&quot; Offset A-End</td>
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<td>String Pot 24&quot; Offset B-End</td>
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<tr>
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<tr>
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<td>String Pot Head B-End</td>
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<td>13</td>
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<td>14</td>
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### DOT-117 CORA and RSVVP Scores

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<td>Phase</td>
<td>Magnitude</td>
<td>Slope</td>
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<td>Impactor Displacement</td>
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<tr>
<td>7</td>
<td>String Pot 0&quot; Offset</td>
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<td>0.9</td>
<td>0.98</td>
<td>0.89</td>
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<tr>
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<tr>
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<td>0.96</td>
<td>0.97</td>
<td>0.87</td>
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<td>0.98</td>
<td>0.97</td>
<td>0.78</td>
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<tr>
<td>11</td>
<td>String Pot Head A-End</td>
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<td>0.93</td>
<td>0.98</td>
<td>0.93</td>
</tr>
<tr>
<td>12</td>
<td>String Pot Head B-End</td>
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<td>0.91</td>
<td>0.99</td>
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<tr>
<td>13</td>
<td>String Pot Skid A-End</td>
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<tr>
<td>14</td>
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<td>0.83</td>
<td>0.99</td>
<td>0.81</td>
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</table>
CORA and RSVVP Score Comparison

• Individual CORA scores were closer to failure than RSVVP scores
  – However CORA recommends only pass/fail with overall score
• RSVVP recommended only Sprague-Geer comparisons for velocity and displacement and ANOVA comparisons for acceleration and force
  – However comparisons were for all cases for discussion purposes
• RSVVP did not recommend use of a slope score
  – CORA’s slope scores were generally closer to failure than other individual CORA scores
• RSVVP included a variance score for normalized residual error
Force-time History (DOT-105)

- DOT-105 tank car punctured in the test (red) at 0.23 seconds but model (black) predicted puncture at 0.21 seconds
  - Early puncture only penalized up to point of model termination
- Force calculated from acceleration but scores are the same due to normalization
- RSVVP does NOT recommend Sprague-Geer comparisons for acceleration

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|}
\hline
\hline
 & \textbf{Corridor} & \textbf{Cross-Correlation Rating} & \textbf{Overall} & \textbf{Sprague-Geer} & \textbf{ANOVA} \\
 & & \textbf{Phase} & \textbf{Magnitude} & \textbf{Slope} & \textbf{Magnitude} & \textbf{Phase} & \textbf{Overall} & \textbf{Error} & \textbf{STDEV} \\
\hline
Impactor Force & 0.93 & 0.76 & 0.97 & 0.27 & 0.77 & 0.04 & 0.05 & 0.07 & 0.03 & 0.11 \\
\hline
\end{tabular}
\end{table}
• DOT-117 tank car did not puncture in the test (red) or model (black)
  – Qualitatively DOT-117 agreement looks better than DOT-105 but scores are similar
• Slope scores were poor for both DOT-105 and DOT-117

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Impactor Force</td>
<td>0.91 0.83 0.97 0.51 0.83</td>
<td>0.02 0.04 0.05 0.01 0.09</td>
</tr>
</tbody>
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Early Termination Due to Puncture (DOT-105)

• Modeling the impact after puncture is computationally expensive because tearing must occur in solid elements
  – Over 1 million brick elements in some cases
• Models typically terminate shortly after puncture and validation scores are NOT calculated between the time the models puncture and puncture occurs in the test
  – Results in artificial score inflation
• Some scores should be computed at least until puncture occurs in both the test and model
  – If puncture does not occur, then some point after impactors rebounds in both test and model
Peak Value Comparison (DOT-105)

- Early model termination can artificially inflate scores
- Simple peak value comparisons unaffected but no information on phase or point-to-point comparison

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<table>
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<tr>
<th>Signal</th>
<th>DOT-105</th>
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<tr>
<td>String Pot Vertical</td>
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<td>Signal</td>
<td>Corridor</td>
<td>Cross-Correlation Rating</td>
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<tr>
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<td>Phase</td>
<td>Magnitude</td>
</tr>
<tr>
<td>String Pot Vertical</td>
<td>0.99</td>
<td>0.86</td>
</tr>
</tbody>
</table>
Change in Air Pressure-time History (DOT-105)

- Typically pressure is reported with respect to atmospheric pressure (psig) but this resulted in unrealistically high scores due to built-in normalization.
- Scores computed using change in pressure to avoid inflation.
  - Start at zero.

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<td>Change in Air Pressure</td>
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• More complex modeling technique (Lagrangian EOS) of fluid required for low outage tank
  – Increases CPU time
• Phase disagreement was heavily penalized by CORA but not by RSVVP
• Tape switch triggers are used during test to determine start of impact so automatic time shifting performed by RSVVP was deemed unnecessary
• Disagreement in phase is likely due to difficulty in modeling friction between skid and ground

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<td>Phase</td>
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<td>String Pot Head B-End</td>
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<td>0.63</td>
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</table>

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Summary of Validation Metrics

- **Magnitude**
  - Dynamic Time Warping (DTW) in CORA seems to work better than Root Mean Squared (RMS) comparison in RSVVP

- **Phase**
  - Iterative shifting followed by zero normalized cross correlation in CORA seems to work better than normalized cross correlation by itself in RSVVP

- **Slope**
  - Slope metrics in CORA seem very difficult to score well for high frequency signals (acceleration = poor / displacement & velocity = nearly perfect)

- **Corridor / Error**
  - RSVVP and CORA perform similar calculations for residual error (<5%) but CORA gives partial credit for residual error up to (50%), i.e. inner and outer corridor
  - RSVVP does not recommend performing error calculations on velocity, displacement, and other integrated values due to accumulation of residual error
    - However the DOT-105 and DOT-117 models received very good error scores for velocity and displacement
Future Work

1. Continue research on validation of tank car side impact puncture models

2. Propose standardized model validation procedures and criteria for industrial use
Further Reading

More information available online at:

Dynamic Time Warping (DTW)

- Algorithm for comparing similarity of two signals
  - Well known application in speech recognition to handle different speaking speeds
- Method that calculates optimal match between two time signals
  - Each index from a signal can match with multiple indices (dilation annotated in figure) from other signal
- Works well for making point-to-point comparisons of signal magnitude