VALIDATION OF METHODOLOGY TO EVALUATE RISK REDUCTION IN TANK CAR DERAILMENTS

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ABSTRACT
Critical derailment incidents associated with crude oil and ethanol transport have led to a renewed focus on improving the performance of tank cars against the potential for puncture under derailment conditions. Proposed strategies for improving accident performance have included design changes to tank cars, as well as, operational considerations such as reduced speeds.

In prior publications, the authors have described the development of a novel methodology for quantifying and characterizing the reductions in risk that result from changes to tank car designs or the tank car operating environment. The methodology considers key elements that are relevant to tank car derailment performance, including variations in derailment scenarios, chaotic derailment dynamics, nominal distributions of impact loads and impactor sizes, operating speed differences, and variations in tank car designs, and combines these elements into a consistent framework to estimate the relative merit of proposed mitigation strategies.

The modeling approach involves detailed computer simulations of derailment events, for which typical validation techniques are difficult to apply. Freight train derailments are uncontrolled chain events, which are prohibitively expensive to stage and instrument; and their chaotic nature makes the unique outcome of each event extremely sensitive to its particular set of initial and bounding conditions. Furthermore, the purpose of the modeling was to estimate the global risk reduction expected in the U.S. from tank car derailments, not to predict the outcome of a specific derailment event.

These challenges call into question which validation techniques are most appropriate, considering both the modeling intent as well the availability and fidelity of the data sets available for validation. This paper provides an overview of the verification and validation efforts that have been used to enhance confidence in this methodology.

INTRODUCTION
Given the recent accident history associated with hazardous material transport, the tank car community has focused on improving the puncture performance of tank cars under derailment conditions. As the shipment by rail of hazardous material, particularly crude oil, has gone up, this focus on safety improvements, either through changes in tank car design or train operations has further intensified.

Among other things, this safety effort has focused on improving the design of tank cars and/or limiting operating speeds, as methods to enhancing safety. As the tank car community reviews potential mitigating strategies/solutions for implementation, it becomes critical to have an objective measure of the expected improvements (i.e., reductions in risk or probability of puncture) that these solutions afford. While, the industry has made progress on analytical techniques for quantifying puncture resistance for specific designs and specific impactor sizes, objective mechanisms to translate these analyses into overall safety improvement are still needed.
Tank cars are exposed to a wide range of hazards during derailments, including a range of different impactor sizes, impactor shapes, impact speeds, etc., making it difficult to quantify the overall, ‘real-world’ safety improvement from any given mitigating strategy, whether it be a design improvement or a safer operational strategy.

Prior work [1, 2] developed a methodology to estimate the relative safety benefits (i.e., risk reduction) resulting from changes in tank car designs, braking systems, or operating conditions under derailment conditions, focusing on the likelihood of a tank to puncture (and thus release hazardous materials). The methodology captured several elements/parameters relevant to derailment and puncture performance, and combined them into a consistent probabilistic framework to estimate the relative merit of proposed mitigation strategies to improve tank car puncture performance.

Comparison of the estimates from this methodology to actual derailment data indicated that the gross dynamics of a tank car train derailment, and the resulting puncture performance of the tank cars are captured well by this methodology. In addition, model estimates regarding the number of cars derailed and number of punctures, as a function of train speed, compared favorably with observed derailment data. This prior validation effort provided confidence that the approach not only captures relative merits but also that the overall puncture probability predictions resulting from this approach are consistent with observed derailment performance.

This paper discusses techniques used for component verification and the challenges related to validation of the methodology. The modeling approach involves detailed computer simulations of derailment events, for which typical validation techniques are difficult to apply. Freight train derailments are uncontrolled chain events, which are prohibitively expensive to stage and instrument; and their chaotic nature makes the unique outcome of each event extremely sensitive to its particular set of initial and bounding conditions. Furthermore, the purpose of the modeling was to estimate the global risk reduction expected in the U.S. from tank car derailments, not to predict the outcome of a specific derailment event.

**DETAILED METHODOLOGY**

The overall methodology is described below and represented schematically in Figure 1.

- Develop a consistent measure of the load environment associated with nominal tank car derailments, through multiple derailment simulations, to derive a histogram of ‘nominal’ impact forces.
- Quantify the puncture resistance of given tank car designs, for a nominal range of impactor sizes and impact forces, from past published research.
- Combine the load environment histograms, the puncture resistance curves, and nominal impactor size distributions, to evaluate the safety performance or probability of puncture for a set of designs and operating conditions.
- Confirm the validity of the methodology through review of engineering expectations and comparisons to historical data.

The methodology was used to estimate the likely number of punctures for a base case (existing tank car design), as well as for proposed mitigating strategies such as a thicker tank shell or reduced operating speeds.

Although the elements of the proposed methodology have not all been previously combined to evaluate risk reduction, individual elements, such as derailment dynamics modeling and tank puncture resistance modeling, are established technical approaches [3, 4]. Additionally, the car puncture resistance curves for several conventional designs have already been developed and published by the FRA [5], thereby lending higher confidence to the approach undertaken.

**Modeling the Derailment Scenarios**

The load environment associated with derailment events is not easily quantified. While one can broadly infer the magnitude of forces involved in a derailment after the event has occurred, there is little or no data available on the specific impact loads that are generated during a derailment event. Each derailment event generates not one, but a spectrum of forces, as each tank car is impacted by other tank cars in its vicinity, as well as by other objects in the vicinity of the derailment site. Given the lack of empirical (or other) data associated with derailment loads, this approach has estimated the forces generated during a derailment through detailed computer simulations of derailment events. These computer simulations have modeled the derailment dynamics of a tank car train operating at a given speed by initiating the derailment event through a brief, externally applied force on the leading car and
then letting the derailment unfold, as defined by the physical circumstances of that derailment.

Simulation of derailments requires the use of a finite element modeling program with an explicit integration mechanism, and the capability to incorporate complex contact algorithms, nonlinear material models, and nonlinear dynamics. LS-DYNA3D [6] is an explicit finite element solver that meets these requirements and was used for all the derailment simulations reported here.

The derailment scenarios were simulated on level, tangent track, with the leading truck of the first car subjected to a brief lateral force to initiate the derailment. Upon initiation of derailment, a retarding force equivalent to an emergency brake application is imparted to all the cars, propagating from the front (point of derailment) to the rear of the train, for a train with conventional brakes. Figure 2 presents the results of one simulation, showing the post-derailment state of the cars, which is generally consistent with the ‘accordion’ type pile-ups observed in many actual derailments (see, for example, the aerial view in accident report NTSB/RAR-12/01 [7]).

![Image of a pile-up resulting from a simulated derailment at 30 mph](image)

**Figure 2. Example of a pile-up resulting from a simulated derailment at 30 mph**

**Derailment Load Spectrum**

As noted earlier, the intent of this effort was to evaluate the effect of a given mitigating strategy in a ‘global’ sense, rather than focus on a specific event or set of circumstances. A key goal was to make sure that the results of this effort could be applied broadly, and this required the development of a force spectrum that could be associated with a universal ‘nominal’ derailment, rather than a specific one. However, collision or derailment events are chaotic, and, depending on the specific circumstances of a given derailment, can unfold very differently. Among other factors, the specific sequence of events and impact loads associated with a derailment could vary depending upon:

- **The terrain where the derailment occurs**: a derailment in the muddy soils of the southeastern US, could unfold quite differently compared to a derailment on the frozen ground (during winter) of the northern states.

- **The speed of derailment initiation**: the higher the speed at the point of derailment initiation, the higher the kinetic energies are, and thus, higher forces and damage levels are expected.

- **The severity of derailment initiation**: this represents an ‘initial condition’ for the derailment; variations in whether the derailment was initiated by a ‘gentle’ wheel climb or by a more abrupt event, such as track or equipment failure, would result in different derailment sequences.

- **The quality of track**: flexible track of poor quality could lead to more cars jumping the rail once a derailment is initiated, compared to a higher quality, stiffer track, which can provide a higher level of lateral restraint.

In order to derive a ‘nominal’ force spectrum, not from the simulation of a single derailment but rather from a set of derailments that reasonably represent the variations in conditions outlined earlier, a series of simulations were run varying the following parameters:

- Coefficient of friction between tank cars and ground, representing multiple terrain conditions,
- Initial train speeds (speed at time of derailment initiation),
- Lateral force to initiate derailment,
- Lateral track stiffness, representing variations in track quality.

Each simulation results in several impacts between the involved cars. The forces generated at each impact (between any two cars) are analyzed to generate a histogram of forces associated with that derailment simulation. The histograms from all simulations were accumulated and then averaged over multiple simulations at each speed to generate a histogram of impact forces that might be experienced during a ‘nominal’ 30 mph, 40 mph or 50 mph derailment. Figure 3 presents this ‘nominal’ force histogram for each of these initial train speeds.

![Image of impact loads resulting from derailments at various initial train speeds](image)

**Figure 3. Histogram of impact loads resulting from derailments at various initial train speeds**
As observed, each histogram approximates a normal distribution with lower force impacts being more frequent and higher force impacts being less frequent. It can also be observed that the increased speeds result in more numerous impacts at all force levels as well as impacts of higher force (and thus consequence).

**Tank Car Puncture Resistance Capacity**

The capacity of a given tank car design to resist impact is dependent on several elements of its design. For conventionally designed steel tank cars (which is the focus of the current effort), it is fundamentally based on the thicknesses of the key elements (shell, head, jacket, etc.), and the material properties of the steel used. The FRA (and industry) have sponsored several studies that have resulted in the development of detailed and reasonably validated models that have characterized the capacity of a given tank car design to resist an applied impact force, considering the size of the impactor.

Consider the example chart presented in Figure 4 [5]. Such charts were developed to characterize the puncture resistance of different tank car designs, ranging from base-level DOT-111 tanks to modern tank designs that are intended for carrying Poisonous-by-Inhalation (PIH) materials. The results are based on detailed finite element analyses of tank shells and tank heads, under a variety of puncture conditions, including various impactor sizes. A characteristic length that is the square root of the area of the impactor face defines these impactor sizes.

Figure 4. Capacity of tank car to withstand impact

For a baseline DOT-111 tank car (7/16” A-516-70 tank shell, no jacket), represented by the green line in Figure 4, a three-inch impactor will puncture the tank at a little over 200,000 pounds. A six-inch impactor would not puncture the tank until the force levels approach 400,000 pounds. Essentially, the chart defines the force level at which a given impactor would puncture the tank shell. Alternately said, the chart defines the impactor size that would result in tank puncture for a given force level.

**Impactor Distributions**

Under derailment conditions, a given tank car may be subject to impacts from a variety of impactors, including broken rail, coupler heads and shanks, wheels/truck components, as well as blunt impact from other tanks. These impactors vary in size, ranging from less than 3 inches to more than 12 inches, and it is difficult to gather consensus on what a “nominal” impactor is. Given that smaller impactor sizes increase the chances for a tank shell puncture, assuming too small an impactor size can lead to very conservative results, and assuming too large an impactor size can lead to risk underestimation. In this approach, the actual impactors are not explicitly modeled; rather, a distribution of impactor sizes is assumed. In reality, there is wide distribution of impactor sizes, and this was the approach adopted for this effort. For these analyses, the impactor distribution shown in Figure 5 was used.

Figure 5. Assumed impactor size distribution

This distribution assumes that a large majority of impactors (about 71%) are in the range from 3 to 9 inches, with a small fraction of impactors (3%) being smaller, and the rest being larger. About 5% of the impactors were considered to be blunt (other tanks). These assumptions are discussed further in the Calibration section.

**Likelihood of Puncture**

With the load histograms, car capacities, and impactor distributions in place, the likely number of punctures for a given car design can be calculated. The process is as follows:

1. For the car design being analyzed (all tank cars in the train are assumed to be identical), the appropriate car capacity curve (such as those in Figure 4) is selected based on car design.
2. For each load magnitude (bin) in the load histogram, the associated impactor size that will result in car puncture is evaluated from the car capacity curve.
3. The proportion of impactors that fall below that size threshold, based on the distribution of impactors (Figure 5), represents the probability that a load of that magnitude will result in a car puncture.
4. Probabilities are then combined with the number of collisions in the corresponding magnitude bin.
5. By accumulating this probability over all the load bins in the histogram, the probability of any specific number of punctures is calculated.
6. The number of punctures with the highest probability (the most likely number of punctures) is a measure of the damage severity.

As an example, Table 1 presents the results of such an analysis for two different car designs at two different derailment initiation speeds. The resultant comparisons between tank car designs, as well as between speeds, allows one to evaluate the relative merits of each mitigating strategy.

<table>
<thead>
<tr>
<th>Table 1. Model Estimates for Likely Number of Punctures</th>
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<tbody>
<tr>
<td>Speed mph</td>
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<tr>
<td></td>
</tr>
<tr>
<td>7/16&quot;</td>
</tr>
<tr>
<td>No Jacket</td>
</tr>
<tr>
<td>Most likely number of punctured cars</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>% Improvement compared to base case</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>40</td>
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<tr>
<td>% Improvement due to speed reduction</td>
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<tr>
<td>40 to 30</td>
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</table>

As observed, the model is predicting that an alternate tank design with a 9/16 inch TC128 shell, 11 gauge jacket and full-height head shield will perform 52% better than a base DOT-111 car in a 40 mph derailment. The model also predicts that the same alternate car will be 42% more likely to survive if the derailment happened at 30 mph rather than 40 mph.

In summary, the methodology presented above estimates the relative merits of multiple strategies proposed to improve tank car safety, whether it is in the form of car design improvements or operational restrictions. The next challenge is verification and validation of the methodology.

**CALIBRATION**

As explained previously, the key output of the DOT methodology is the number of punctures, and the three main inputs into the calculation of number of punctures are:

- Derailment load spectrum, derived from simulations
- Car strength characteristics
- Impactor size distribution

This section describes methods and sources used to calibrate the parameters that were used to model these phenomena.

Data from physical testing was used to calibrate the emergency brake system response following train separation upon derailment. Testing was conducted under both laboratory and field conditions. This included a revenue service train configured with distributed power (DP) and conventional brakes, and a brake test rack with electronically controlled pneumatic (ECP) brakes. Emergency signal transmission and latency times were measured, as well as the brake cylinder pressure build-up curves for both conventional and electronic brakes. Piece-wise linear representations of this information were incorporated into the derailment simulation models for the various brake system types. Proper implementation of the braking model was verified by extracting the brake retarding forces applied to each car from the LS-DYNA derailments runs. The reported force time histories exactly matched the input load curves derived from the field and lab test data.

Car strength characteristics were extracted from prior analyses done by Kirkpatrick [5], and presented in prior papers and reports. These curves (as shown in Figure 4) essentially represent the force at which a car of a given design would puncture as a function of the impactor size. These research efforts have been sponsored by both the DOT and industry and are well regarded. The analytical methods used by Kirkpatrick have been validated through multiple physical tests. Therefore, the DOT has confidence that this input is justified.

The impactor size distribution (Figure 5) considers a variety of impactor sizes nominally encountered in a derailment incident. Qualitatively, this spectrum is consistent with puncture sizes observed by DOT accident investigators from several derailments, wherein, most punctures are in the 5 to 9 inch range, consistent with a coupler or a sill type impact. Rail induced punctures tend to be fewer given the lack of stiffness/mass associated with rail structures and the smaller fraction of related impactor sizes reflects this reality. In general terms, impactor sizes can be categorized as follows.

- Broken rail impactors are likely to be in the range of 2 to 7 inches,
- Coupler shanks are likely to be around 4 to 8 inches,
- Coupler heads are likely to be around 9 to 12 inches,
• Truck components could be in the range of 9 to 16 inches,
• Bulk impact could be larger than 24 inches,
• Any of the above impactors could present a smaller face under oblique impact angles.

In addition, work done under the Advanced Tank Car Cooperative Research Program (ATCCRP), and sponsored by industry, has generated a similar, but, probabilistic impactor size distribution. The average impactor size from this work (8.4 inches) is less than 4% off the average impactor size used in the subject methodology (8.7 inches). These observations offer confidence that a reasonable impactor size distribution was used.

VERIFICATION

The tank car puncture risk methodology was verified at many steps throughout the development process. The first step was to ensure that the dynamic derailment simulations were predicting reasonable and consistent results. As mentioned previously, the widely used computer program LS-DYNA was used to model the simulated derailment dynamics and extract the impact forces. Due to an extensive history of comparing LS-DYNA simulations of simple mechanics problems to their known analytical solutions, LS-DYNA can be considered verified for general nonlinear dynamic contact/impact problems [8].

Simple computational checks were performed within LS_DYNA to assure that the model obeyed energy conservation laws and the levels of hourglass energy, added mass, and system damping remained below 5% of total energy. Outputs describing modeled features, such as frictional forces between tanks and the ground, and coupler angles and moments at joint failure, were checked for consistency with the corresponding input values.

One of the unique aspects of a train derailment is the chaotic nature of the resulting pile-up. A long string of 100 cars in compression is essentially a buckling problem as it breaks free from the lateral constraints of the track. The unfolding dynamics can take place over many hundreds of feet with durations well over 30 seconds (depending on the initial speed, terrain, etc.). Small differences in the initiation of the buckling can produce very different results in terms of pile-up configurations. In addition, the results are also extremely sensitive to randomness of numerical round-off. Identical inputs can produce different output when the same model is run on different computer operating systems or on the same system with different number of processors. For this reason, all LS-DYNA simulations in this methodology were run with a single processor and with the “consistency flag” set on. This produces nearly identical results between runs by controlling the precise order of vector summations [6].

CONFIRMATION OF TRENDS AND EXPECTATIONS

Additional verification is derived from confirmation that trends of the model’s predictions are in line with expectations. Confidence in the model is enhanced when it responds appropriately to specific changes in the input parameters, as evidenced by the following observations (some of these are discussed further in the Validation section).

• The number of impacts increases with increasing speed (impact load histogram, Figure 3),
• The maximum value of the impact force increases with increasing speed (Figure 3),
• The average number of cars derailed increases with increasing derailment speed (Figures 6 and 7),
• The spread of the number of cars derailed, among each set of 18 simulations, increases with increasing speed (Figure 6),
• Higher derailment initiating force leads to more cars derailing,
• Higher lateral track stiffness leads to fewer cars derailing,
• The average number of cars punctured increases with increasing derailment speed (Table 1 and Figure 8),
• The number of cars punctured reduces with improved car design (Table 1),
• The change in number of cars punctured is somewhat proportional to the change in the combined car shell and jacket thicknesses (for similar material strengths). This is consistent with the physics of puncture, and has also been demonstrated in prior work by Kirkpatrick and the Volpe Center.

These trends are in line with expectations from physics and are consistent with derailment observations.

VALIDATION

To ensure the applicability of the results from any proposed methodology, a reasonable validation of the methodology is key. Naturally, the steps taken towards validation might take different forms depending upon the particular issue being studied, and importantly, the availability of accurate real-life or test data with which a validation effort can be initiated.

Unlike the typical approach used to test hypotheses associated with statistical models, this methodology is not trying to create an empirical model by fitting to existing derailment data. The physics of rail car derailment and pile-up is well understood, albeit complex and chaotic and thus hard to predict or recreate for a specific, unique instance. The goal of the methodology is to capture phenomena that affect the puncture of rail car tanks during derailments in order to evaluate the global consequences (with respect to derailment damage) of various mitigating strategies. So, validation against specific derailment events, while desirable, is not necessary; validation against global measures associated with the damage caused by tank car puncture and release of flammable liquids is
more relevant. However, this type of data is not readily available and conducting full scale derailment tests is not feasible. Given the intent of the methodology and constraints on available data, model confidence was enhanced by addressing the following validation elements.

- Prediction of the number of cars derailed as a function of initial train speed,
- Prediction of the number of punctures as a function of initial train speed,
- Regression analysis to confirm that key parameters were considered,
- Comparison with a specific derailment event,
- Comparison with other studies.

**Dynamic Model Validation**

There are no historical records of the force levels associated with tank car punctures under derailment conditions; however, data on the number of cars derailed in a given incident are available. Figure 6 compares the number of derailed cars vs. train speed estimated from the derailment simulations conducted as part of this effort to derailment data from the FRA-RAIRS database. As evident from the figure, the simulated predictions of number of cars derailed are consistent with the spread seen in actual derailment data.

**Figure 6. Number of cars derailed vs. train speed – all derailments**

Figure 7 presents a similar comparison only using data from recent major tank car derailments involving hazardous materials (flammable energy liquids). Once again, the average of the predictions is in line with the observed data.

**Figure 7. Number of cars derailed vs. train speed – hazmat derailments only**

These comparisons lend validity to the derailment simulations, confirming that the dynamics predicted by the simulations are consistent with real-life observations. Critically, they also demonstrate that the simulations are not just a single point of reference, but rather, they represent a diverse variety of circumstances, lending credence to the notion that the resulting force histograms are also representative of ‘nominal’ derailments.

**Validation of Puncture Estimates**

The estimates of likely number of punctures were also compared to actual derailment data. Figure 8 presents the model estimates compared to the actual number of cars punctured in recent major tank car derailments (using the same set of derailment data as presented in Figure 7). Several of the trains in this dataset were either unit trains (all tank cars) or contained a long string of tank cars, configurations very similar to those simulated.

**Figure 8. Estimates of likely punctures compared to hazmat derailment data**
The actual derailment data has a wide scatter band; however, the predictions of the model are in line with the ‘nominal’ values. In fact, the average number of punctures predicted for each of the speeds simulated fell very close to the linear fit of the observed derailment puncture data. Overall, the validation effort shows that the methodology predicts gross derailment dynamics and puncture risk estimates that are consistent with observed derailment data.

Regression Analysis

A multi-variate regression analysis was conducted to ensure that the methodology included, and focused on, the parameters that were key to the derailment performance of tank cars. The analysis queried accident data from the Federal Railroad Administration’s (FRA) Railroad Accident and Incident Reporting System (RAIRS) database for the accidents reported between 1975 and 2016. The data was filtered to account for conditions that were in line with the derailments being studied, and a multivariate regression model was used to determine factors that have significant impact on derailment damage predictions.

The raw data from RAIRS was filtered to only include accidents with:
- Train speed more than or equal to 5 mph
- Only freight trains (passenger trains not considered)
- Only main line tracks or sidings (incidents in yards not considered)
- Total number of cars in the train more than or equal to 10
- Gross tonnage of train between 300 tons and 40,000 tons (this is just a ‘sanity’ check to ensure that incorrect, extreme values are avoided; a 300 ton train would be less than 2 cars long and a 40,000 ton train would be over 250 cars long)
- Only derailments (collisions were not considered)

The following were excluded from the analysis dataset:
- Duplicate entries
- Remotely controlled locomotives
- Inconsistent/missing entries

Post-filtering, there were 42,526 derailment records in the analysis dataset. Of the available parameters, ‘accident severity’ was best represented by the parameter ‘total reportable damage cost’, and the contributions of several predictors in the data to ‘accident severity’ were then tested. It was seen that ‘Train speed’ and ‘total number of derailed vehicles’ were the biggest contributors (14.5% and 31%, respectively) to the variation in ‘damage cost’, and that other predictors were not significant.

Since the number of derailed vehicles is an output of the derailment simulation (and therefore cannot be independently varied as an input to the model), other independent predictors of this parameter were sought. A similar regression analysis was used to investigate the factors contributing to the ‘total number of derailed vehicles’. It was seen that ‘Train speed’ (10%), ‘accident cause’ (10%) and ‘Train size’ (7%) are the top predictors of the ‘number of derailed vehicles’. Therefore, train speed is the single most significant predictor. Predictors of secondary importance include:
- Train Length or Position in train of first derailed car (closer to the front implies greater overall damage)
- Total train tonnage (which correlates well with ‘Train Length’)
- Accident Cause

Other individual factors are insignificant. Most of the variation in derailment damage cannot be explained by factors that are currently available in existing accident databases.

All of the significant factors identified by this analysis were considered as inputs in the overall methodology.

Each simulation is based on a specific train speed. The DOT used 30, 40, and 50 mph to cover the bulk of train operating speeds. This range of speeds is consistent with the speeds of several recent derailments, particularly, ones with a notable potential for damage. For the RIA calculations, the benefit (or risk reduction) at other speeds could be reasonably interpolated or extrapolated. Also, these speeds represent the speed of the train when the derailment was initiated, and not the relative velocity between impacting cars. These speeds were selected not because they represented an ‘average’ or ‘most likely’ value, but rather so that they provide a matrix of results from which risk reduction values for the RIA (whether it is from a tank car design change, operating speed change, or brake system change) can be reasonably evaluated.

Train length is considered in the DOT method by including simulations with varying number of cars, representing derailment initiation at various locations within the train. As with the train speed, the effect of varying the train length was studied by using values of 100 cars, 50 cars, and 20 cars for the train length. Please note that the train length represents the portion of the train that is behind the point of derailment; for example, a 50 car train length would represent a mid-train derailment of a 100 car train, as well as a derailment occurring at the 31st car of an 80 car train. This provides a results matrix and values for other train lengths were reasonably interpolated as part of the RIA calculations.

About two thirds of the ‘accident cause’ types that are most strongly correlated with the ‘number of derailed vehicles’ are attributed to track and roadbed.

The method of derailment initiation in the DOT simulations (lateral impulse applied to lead truck of first car behind the point of derailment sufficient to overcome the rail restraint) is consistent with ‘accident cause’ of track failures, such as broken rail and wide gauge, as well as wheel climb.
Validation against specific derailment event

The DOT methodology was designed and intended to capture the relative performance benefits of car designs, speed reductions, or brake system advancements. It was not intended to capture puncture performance at an individual simulation level. Nevertheless, the simulation of an actual incident was performed and the simulation results were compared with observations from the actual incident. The derailment of a loaded oil train at Aliceville, AL was chosen because, in addition to data on number of punctures and cars derailed, the distance travelled by the rear portion of the train that remained on track was available from the event recorder on the remote DP unit at the rear of the train. Details of the Aliceville derailment:

- 90 cars, loaded oil train
- 2 head-end locomotives, 1 DP locomotive at rear
- 38 mph, derailment initiated at head end of train
- Level grade, track on raised embankment
- Rear locomotive travelled 1,240 feet

The DOT derailment simulation was initiated at the head end of a 100-car, loaded, DP train at 40 mph. Results of several metrics are presented in Table 2.

<table>
<thead>
<tr>
<th>Table 2. Aliceville derailment – comparison with simulation</th>
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<tbody>
<tr>
<td>Cars Derailed</td>
</tr>
<tr>
<td>Aliceville</td>
</tr>
<tr>
<td>FRA Model</td>
</tr>
</tbody>
</table>

The number of cars derailed and distance travelled by the rear locomotive match extremely well. The total number of punctures predicted by model is somewhat below the Aliceville number, but the Aliceville incident is an outlier in this respect (with punctures higher than normal, as shown in Figure 8), perhaps because the cars fell from a raised embankment.

Figure 9 compares the pile-up patterns between the actual incident and the DOT simulation. While it is difficult to make pile-up comparisons without detailed geometric data, it can be observed that the model faithfully represents the characteristic saw-tooth buckling and compact groupings as seen in the actual derailment.

Figure 9. Aliceville pile-up configuration – comparison with derailment simulation

The combination of multiple close correlations between the pile-up configurations, the number of derailed cars, the number of punctures, and the distance travelled by the rear locomotive, provides confidence in the validity of the FRA modeling methodology.

Comparison with other studies

An inspection of the derailment load histograms (Figure 3) shows that the impact force magnitudes are in line with expected force magnitudes that would cause punctures in real life, based on the various impact tests that have been conducted [5].

Predictions from the DOT methodology were also compared to:
- Derailment models developed by the Volpe Center [9],
- Conditional Probability of Release (CPR) values from the RSI-AAR Report (RA-05-02) [10].

DOT estimates for number of cars derailed under various derailment scenarios were compared with results from two derailment models developed at Volpe (which produced similar results). This comparison is presented in Figure 10. As observed, the results are similar and trends are the same. The differences observed are likely the result of the DOT model allowing for full coupler breakage and separation (as expected in real life), whereas the Volpe model does not.

1 This also effectively confirms that the ground friction values assumed in the simulations are reasonable.
Comparing DOT predictions of improved car strength with values from RA-05-02 suggest that AAR and DOT estimates of CPR benefits of improved car strength are similar. Comparing the performance of a DOT-117 car to a DOT-111 car (due to car construction only):

RSI-AAR data predicts a 50% to 60% reduction in punctures.

The DOT methodology predicts similar reduction in number of punctures (in the mid-50% range when averaged over speeds from 30 to 50 mph).

While the individual CPR values may be higher according to the DOT calculations, this likely represents the fact that the DOT calculations are done over a higher range of speeds (30 – 50 mph), whereas the RSI-AAR values include derailments at much lower speeds.

**SUMMARY**

The DOT has developed a methodology to estimate the relative safety benefits (i.e., risk reduction) resulting from changes in tank car designs, braking systems, or operating conditions under derailment conditions, focusing on the likelihood of a tank to puncture (and thus release hazardous materials).

Comparison of the estimates from this methodology to actual derailment data suggests that the gross dynamics of a tank car train derailment, and the resulting puncture performance of the tank cars are captured well by this methodology. In addition, model estimates regarding the number of cars derailed and number of punctures, as a function of train speed, compare favorably with observed derailment data. Also, puncture risk reduction correlates well with engineering estimates corresponding to increased tank shell thickness and material strength. The validation effort provides confidence that the approach not only captures relative merits but also that the overall puncture probability predictions resulting from this approach are consistent with observed derailment performance.

In summary, several elements of the DOT methodology addressing model confidence have been presented, including:

- Calibration of input parameters,
- Verification that the trends of model prediction are in line with physical expectations,
- Validation against physical derailment data, and comparisons with other studies.

These efforts confirm that the DOT’s confidence in its approach and results does not come from just one point of validation, but is the result of reviewing many elements, including both inputs to and outputs from the methodology.

Overall, this methodology offers an objective approach to quantify and characterize the reductions in risk as measured by reductions in puncture probabilities that result from changes to tank car designs or tank car operating practices.

**FUTURE WORK**

As DOT-117 cars proliferate in the fleet, data regarding their performance in derailment will become available for validation of the method’s prediction regarding design improvements, such as increased tank shell thickness. In addition, collection of data regarding impactor sizes and their distribution should be a part of future derailment investigations involving tank cars.

**ACKNOWLEDGMENTS**

The authors would like to convey our thanks to the late Kevin Kesler, Chief, FRA Rolling Stock Research Division for his support and funding.

Our sincere gratitude is also due to Mr. Karl Alexy, Director, Hazardous Materials Safety, FRA Office of Safety for his technical guidance and encouragement.

**REFERENCES**


