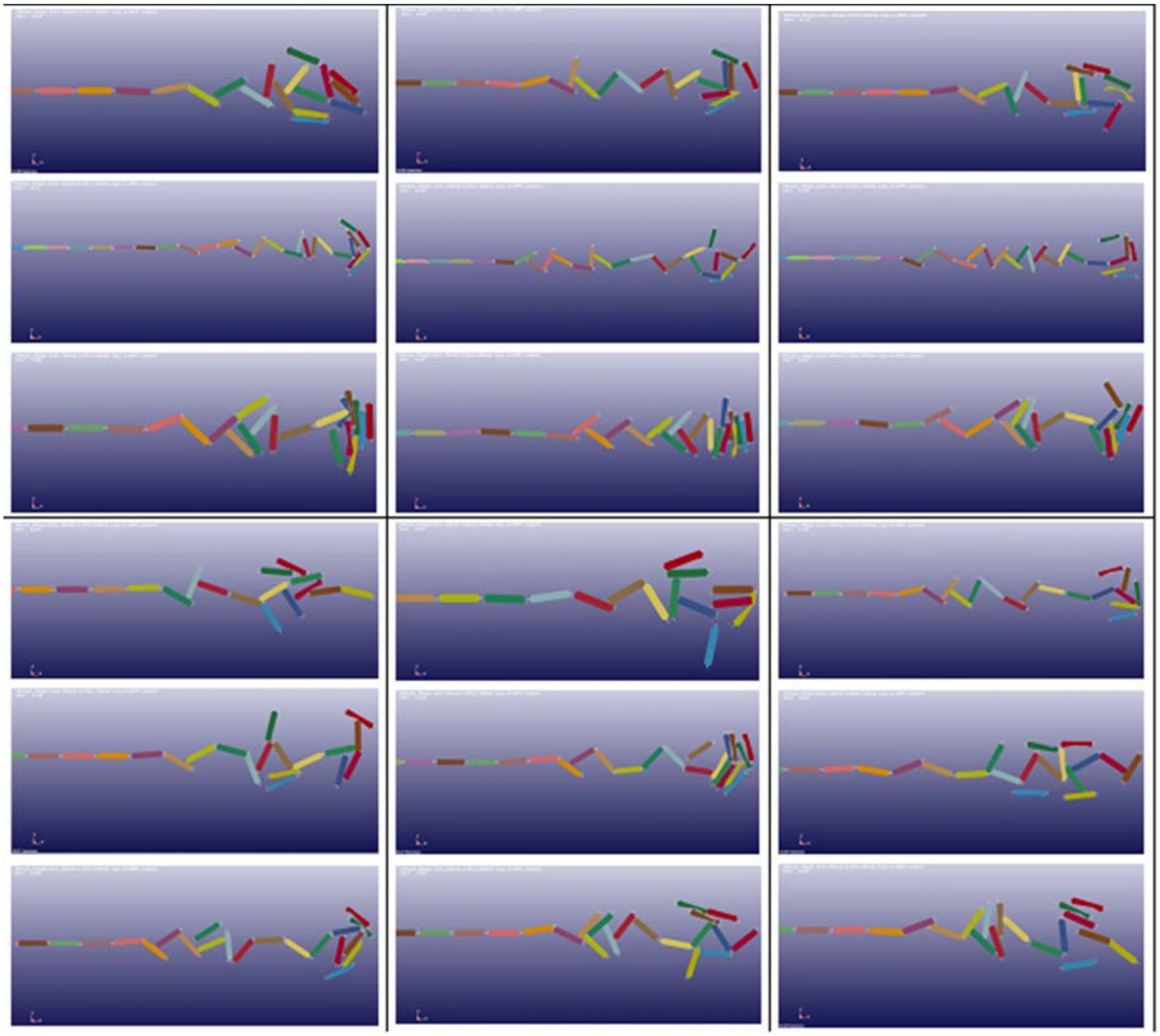
U.S. Department of
Transportation

**Federal Railroad
Administration**

# Objective Evaluation of Risk Reduction from Tank Car Design and Operations Improvements – Extended Study

Office of Research,
Development
and Technology
Washington, DC 20590



DOT/FRA/ORD-18/36

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October 2018

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# METRIC/ENGLISH CONVERSION FACTORS

## ENGLISH TO METRIC

### LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

### AREA (APPROXIMATE)

1 square inch (sq in, in$^2$) = 6.5 square centimeters (cm$^2$)
1 square foot (sq ft, ft$^2$) = 0.09 square meter (m$^2$)
1 square yard (sq yd, yd$^2$) = 0.8 square meter (m$^2$)
1 square mile (sq mi, mi$^2$) = 2.6 square kilometers (km$^2$)
1 acre = 0.4 hectare (he) = 4,000 square meters (m$^2$)

### MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

### VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft$^3$) = 0.03 cubic meter (m$^3$)
1 cubic yard (cu yd, yd$^3$) = 0.76 cubic meter (m$^3$)

### TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

## METRIC TO ENGLISH

### LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

### AREA (APPROXIMATE)

1 square centimeter (cm$^2$) = 0.16 square inch (sq in, in$^2$)
1 square meter (m$^2$) = 1.2 square yards (sq yd, yd$^2$)
1 square kilometer (km$^2$) = 0.4 square mile (sq mi, mi$^2$)
10,000 square meters (m$^2$) = 1 hectare (ha) = 2.5 acres

### MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg)
= 1.1 short tons

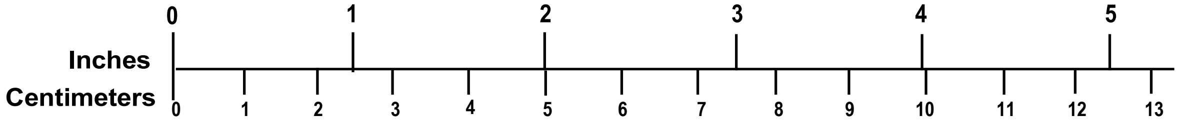
### VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m$^3$) = 36 cubic feet (cu ft, ft$^3$)
1 cubic meter (m$^3$) = 1.3 cubic yards (cu yd, yd$^3$)

### TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

## QUICK INCH - CENTIMETER LENGTH CONVERSION



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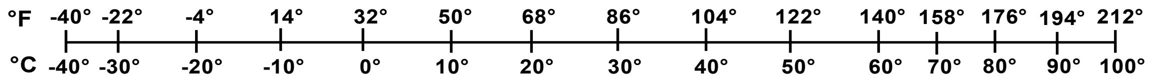

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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# Executive Summary

Given the known accident history associated with hazardous material transport, the tank car community has been focused on improving the performance of tank cars against the potential for puncture under derailment conditions. Proposed strategies for improving puncture performance have included design changes to tank cars, as well as operational considerations such as reduced speeds and improved braking performance. Since puncture hazards have a wide variety of impactor sizes, shapes, speeds, etc., it has been difficult to quantify objectively and globally, the overall 'real-world' safety improvement resulting from any given proposed change.

An earlier letter report on the subject described the prior work [1]. The research was conducted through May 2015 by Sharma Associates, Inc. at their facility with funding from the Federal Railroad Administration. This report describes how this effort was extended to include additional cases, additional speeds, and additional considerations for alternate brake systems. Much of the original descriptive language from this earlier report has been retained to make this document more complete [1].

This report describes an innovative and objective methodology for quantifying and characterizing the reductions in risk (or reductions in puncture probabilities) that may result from changes to tank car designs or the tank car operating environment. The methodology captured several parameters that are relevant to tank car derailment performance—including multiple derailment scenarios, derailment dynamics, impact load distributions, impactor sizes, operating conditions, tank car designs, etc.—and combined them into a consistent probabilistic framework that can estimate the relative merit of proposed mitigation strategies.

For example, the methodology estimated that the impact performance of a proposed tank car design with a 9/16" thick shell, 11-gage jacket and ½" full-height head shield would be over 50 percent better than the performance of a base case Department of Transportation (DOT)-111 tank car. Similarly, the analysis also estimated that reducing the operating speed from 40 mph to 30 mph offered a 42 percent reduction in puncture likelihood for the proposed design. The methodology also estimated that the use of Electronically Controlled Pneumatic (ECP) braking results in about 30 percent fewer punctures during a derailment.

A comparison of the estimates from this methodology to actual derailment data suggested that the gross dynamics of a tank car train derailment and the resulting puncture performance of the tank cars were captured well by this methodology. In addition, the model's estimates regarding the number of cars derailed and number of punctures, as a function of train speed, compare favorably with actual derailment data. Also, puncture risk reduction correlates well with the engineering estimates that correspond to increased tank shell thickness and material strength. These validation efforts improved the credibility of the methodology's efficacy and the results derived from it.

# 1. Introduction

Given the known 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 number of shipments by rail of hazardous material (particularly crude oil) has increased, the focus on improving safety, either through changes in tank car design or train operations, has further intensified.

This safety effort focused on enhancing safety by improving the design of tank cars and limiting operating speeds. As the tank car community reviews potential mitigating 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 towards developing analytical techniques that quantify puncture resistance for specific designs and specific impactor sizes, objective mechanisms to translate these analyses into overall safety improvement do not currently exist.

Tank cars are exposed to a wide range of hazards during derailments, including different impactor sizes, impactor shapes, impact speeds, etc., which makes it difficult to quantify the overall 'real-world' safety improvement from any given change. To objectively compare the overall effectiveness of a proposed mitigating solution, whether it is a thickness increase or an operational change, one needs to measure how the solution is expected to perform in real life against a variety of potential hazards. From a regulatory or a standards perspective, one needs to be able to answer questions such as:

- *What is the overall reduction in risk (or reduction in the probability of puncture) afforded by increasing the minimum required shell thickness to "X" inches?*
- *What is the overall reduction in risk (or reduction in the probability of puncture) afforded by making a given operational change/speed restriction?*

This research effort addressed this with a methodology which calculated resultant puncture probabilities and risk reduction in an objective manner. It connected the load environment under impact conditions to analytical and test-based measures of tank car puncture resistance capacity (which have been further adapted for expected operating conditions). While the methodology is not supposed to predict the precise results of a given accident, it provided a basis for comparing the relative benefits or risk reduction resulting from various mitigation strategies.

An earlier letter report describes prior work on this subject [1]. This report documents additional work done, including the consideration of additional designs, additional operating speeds, and alternate braking systems.

## 2. Overview of Technical Approach

The probability that a given tank car be punctured during a derailment is affected by multiple variables and circumstances, including:

- The derailment scenario, including the speed of derailment initiation, the surrounding terrain, etc. For example, higher derailment initiation speeds tend to lead to more cars derailing as well as higher magnitudes of forces, and thereby, a higher probability of puncture. The surrounding terrain can also have a significant effect on how the derailment unfolds and thus affect puncture probabilities
- The derailment (impact) load spectrum experienced by the tank during the event: the higher the load, the higher the probability of puncture
- The distribution of impactor sizes: the smaller the impactor, the higher the probability of puncture
- The puncture resistance of the tank shell: the thinner the tank shell, the higher the probability of puncture

The approach taken in this report combines the above parameters and circumstances to evaluate the probability that a certain number of tanks of a given design might experience puncture during a derailment event. Rather than focusing on specific values of the above parameters, this approach allows one to consider a nominal distribution of values for each given parameter to ensure that the method is not specific to or biased towards any particular event or circumstance. An overview of this approach is presented in Figure 1. Validation of the model against known historical derailment data is a critical element of the overall methodology.

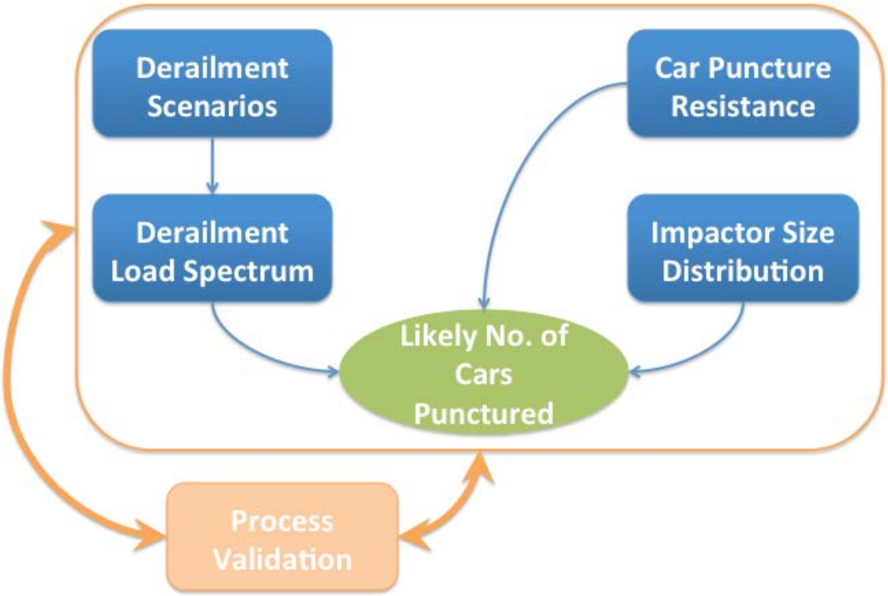

**Figure 1. Overall Concept of Approach**

# 3. Detailed Methodology

The overall methodology outlined below was used to estimate the likely number of punctures for the base case and propose mitigating strategies, such as a thicker tank shell or reduced operating speeds. It does the following:

- Develop a consistent measure of the load environment associated with nominal tank car derailments by using 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 by using past published research.
- Evaluate the safety performance or probability of puncture for a set of designs and operating conditions by combining the load environment histograms, the puncture resistance curves, and nominal impactor size distributions.
- Confirm the validity of the methodology by reviewing engineering expectations and comparisons to historical data.

While all elements of the proposed methodology have not been combined to evaluate risk reduction before, individual elements such as derailment dynamics modeling or tank puncture resistance modeling are established technical approaches [2] [3]. Additionally, the car puncture resistance curves for several conventional designs have been developed and published by the FRA [4], thereby lending higher confidence to the approach undertaken. The following sub-sections outline the methodology in more detail.

## 3.1 Modeling the Derailment Scenarios

The load environment associated with derailments events is not easily quantified. While one can broadly infer the magnitude of forces involved in a derailment event 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 model 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 allowing the derailment to 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 is an explicit finite element solver that meets these requirements and was used for all the derailment simulations reported here [5]. Detailed derailment simulations are inherently computationally intensive.

To optimize computational efficiency without compromising the fidelity of the simulations, the following assumptions were made:

- The trains simulated were composed of up to 100 loaded (to 263,000 lb.) tank cars.

- The cars were individually modeled in three dimensions (3D), with appropriate representation for the tank shells, tank heads, and stub sills. Shell elements with a Belytscko-Tsay formulation were used with a nominal element length of 12 inch, with finer mesh densities where appropriate.
- Trucks and track were not explicitly modeled for this effort; instead, the car center plates were defined to move along the centerline of track through a lateral spring connection between the car and the ground, with the spring stiffness representing a measure of the lateral track stiffness; when the displacement of this spring exceeded a nominal 1 inch, the truck was considered to have derailed and the center plate was subsequently free to move laterally.
- The cars were modeled with deformable TC128 material, and connected with discrete draft gear and coupler models. The coupler models allowed a 7 degree swing in each direction, with the knuckles modeled to resist rotation and fail when the rotation exceeds 13.5 degree, which is consistent with the coupler rotation limits defined for E-type couplers in the AAR Manual [6]
- The tanks were free to move in any direction, while the bolsters and were constrained to move in a horizontal plane (i.e., the tanks were allowed to slide, but not roll over).

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. The retarding force applied was 13,255 lb. per car which represents an emergency associated with a 12 percent Net Braking Ratio (NBR). A pneumatic emergency propagation rate of 950 ft/s was used with a 12 second build up time. In the case of trains equipped with two-way End-Of-Train (2-EOT) devices, the brake signal propagation was initiated at both ends of the train. For trains with ECP, it was assumed that all cars would get the braking signal simultaneously. 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 multiple real-life derailments.

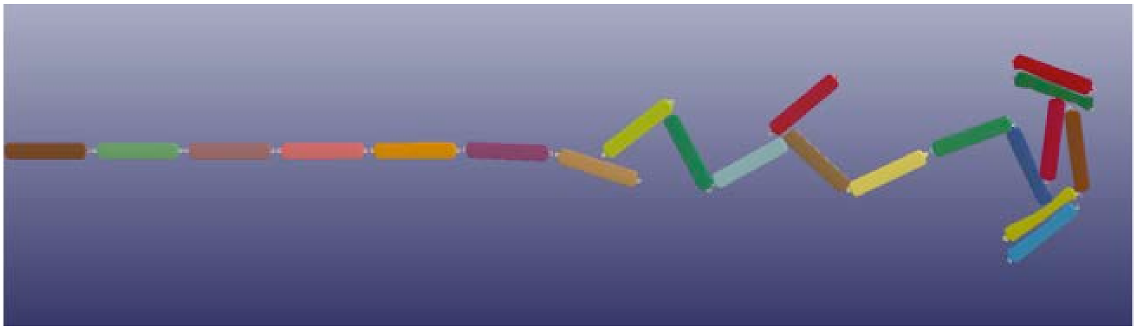

**Figure 2. Example of a Pile-up Resulting from a Simulated Derailment at 30 mph**

As noted earlier, the intent of this effort was to evaluate the effect of a given mitigating strategy in a ‘global’ sense, instead of tying the simulation to 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 can unfold very differently, depending on the specific circumstances of a given derailment. Among others, the specific sequence of events and impact loads associated with a derailment could vary depending on:

- **The underlying terrain where the derailment occurs:** A derailment in the muddy soils of the southeastern US, could unfold quite differently compared to a derailment in 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 the forces and damage levels
- **The severity of derailment initiation:** This represents an 'initial condition' for the derailment and variations in whether the derailment was initiated by a 'gentle' wheel climb, or, a more abrupt event such as track/equipment failure, would result in different derailment sequences
- **The quality of track:** Flexible track of poor quality could lead to more cars jumping 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 from a set of derailments that reasonably represent the variations in conditions outlined earlier, a series of simulations varying the following parameters were run:

- *Three values of coefficient of friction between tank cars and ground to represent multiple terrain conditions: 0.27, 0.30, and 0.33.* This range is consistent with nominal values for friction between steel and soil, which generally range from 0.2 to 0.4. Higher friction values, especially values that are near 1.0 are unrealistic and represent conditions that are closer to 'rubber-on-concrete', rather than 'steel-on-soil.' As an example, a friction level of 1.0 would result in a tank car traveling at 50 mph to decelerate to a stop in 84 ft (less than 1.5 car lengths); there is very little evidence of 50 mph derailments coming to a stop within 1.5 car lengths. Essentially, the range of friction factors used in the analysis is a reasonable blend that allows the relative performance of car designs or mitigating strategies to be evaluated consistently.
- *Three initial train speeds: 30, 40 and 50 mph.* This parameter represented the speed of the train when the derailment was initiated, and not the relative velocity between impacting cars. This range of speeds is consistent with the speeds of several recent derailments, particularly, ones with a notable potential for damage.
- *Three values of lateral force to initiate derailment: 50, 70 and 90 kips.* These values represented a truck side lateral force/vertical force (L/V) ratio of 0.76 to 1.06; a value of 0.6 is considered a safety limit for rail roll over and higher values would be needed to initiate a derailment, as used here.
- *Two values of lateral track stiffness, representing variations in track quality: 30 and 40 kips/in*. The 40 kips/in value represented a truck side L/V ratio of 0.6 at 1 inch of lateral wheel movement, while the 30 kip/in value represented poorer quality track that was 25 percent more flexible

In general, the assumptions made in setting up these and other similar simulations not only reflect physical conditions, but also the preferences of the analyst, as well as requirements for simulation efficiency and speed. This set of simulations is no different, and the authors acknowledge that other analysts and researchers may choose to make different assumptions. Nonetheless, the goal is to effectively evaluate the relative performance of multiple designs and operating conditions, and it is expected that the assumptions made herein will allow for an effective comparison.

## 3.2 Impact Load Spectrum

The permutations and combinations presented above represent 18 different derailment scenarios for each speed. In other words, rather than having a single derailment represent the dynamics and force distribution, the ‘nominal’ force distribution is an aggregation of forces from a ‘family’ of 18 derailments for each initiating speed.

Figure 3 presents, as an example, the final pile-up images for each of the 18 runs for the derailment initiation speeds of 30 mph. As evident from these images, this set of runs reflects a reasonable breadth of derailment scenarios, which supports the contention that this methodology generates a ‘nominal’ force histogram associated with a ‘nominal’ derailment.

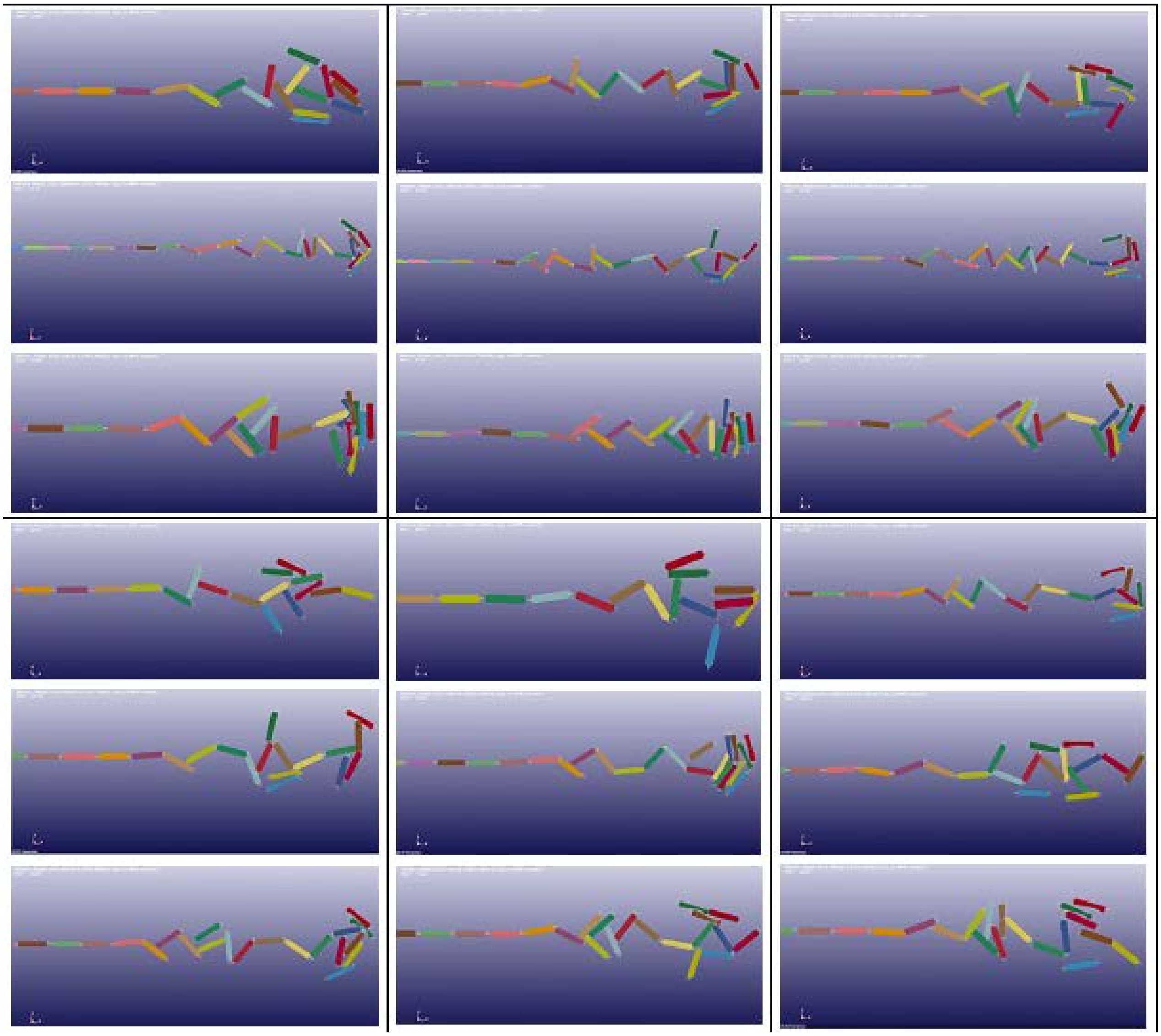

**Figure 3. Distribution of Derailments - Final Pile-ups from 18 Scenarios at 30 mph**

Each simulation results in several impacts between the involved cars. On average, there were about 28 collisions in a 30 mph derailment, about 44 collisions in a 40 mph derailment, and about 61 collisions in a 50 mph derailment. The forces generated at each impact (between any two cars) then analyzed to generate a histogram of forces associated with that derailment simulation.

The histograms from all simulations were accumulated and then averaged over the 18 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 4 presents this 'nominal' force histogram. As observed, the 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).

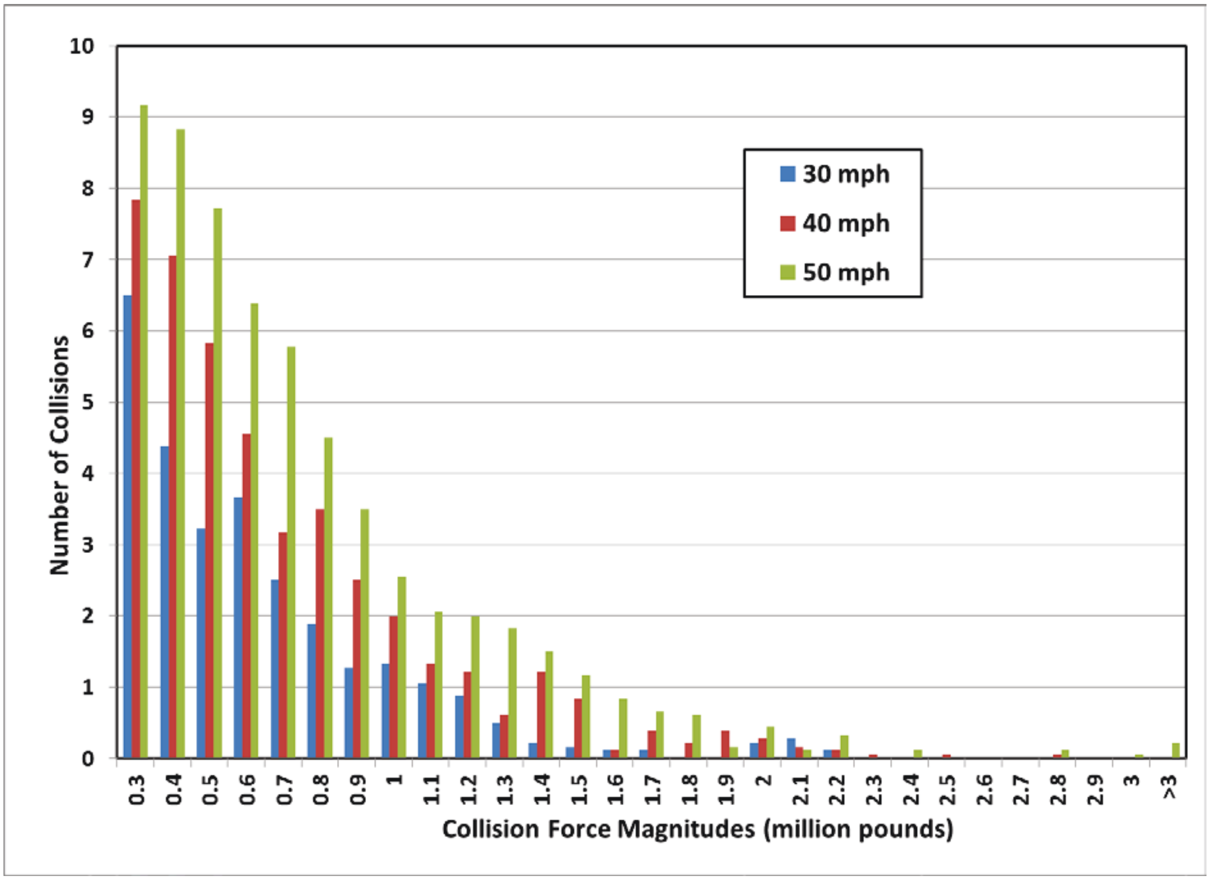

**Figure 4. Histogram of Impact Loads Resulting from Derailments Averaged from 18 Scenarios Per Speed**

## 3.3 Tank Car Puncture Resistance

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. FRA and the industry have sponsored several studies that have led to the development of detailed and reasonably validated models that can characterize 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 5 [4]. Such charts were developed to characterize the puncture resistance of different tank car designs, from base-level DOT-111 tanks to modern tank designs. 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. For a baseline DOT-111 tank car (7/16 inch A-516-70 tank shell, no jacket), represented by the green line in Figure 5, a 3-inch impactor will puncture the tank at a little over 200,000 lb, and a 6-inch impactor would not puncture the tank until the force levels approach 400,000 lb. The chart essentially defines the force level at which a given impactor would puncture the tank shell, or in other words, the chart defines the impactor size that would result in tank puncture for a given force level.

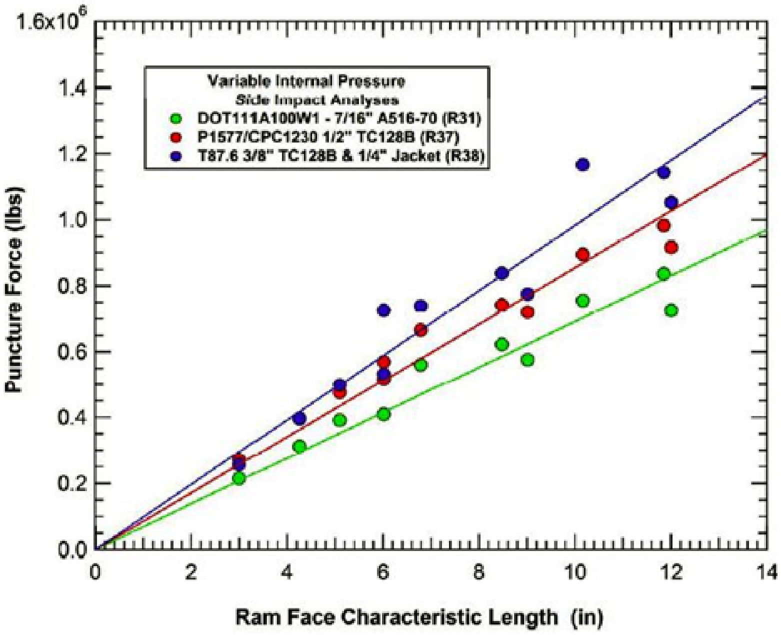

**Figure 5. Capacity of Tank Car to Withstand Impact**

## 3.4 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 inch to more than 12 inch, 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 of 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.

For these analyses, the impactor distribution shown in Figure 6 was used. This distribution assumes that a large majority of impactors (about 71 percent) are in the range from 3 inch to 9 inch, with a small fraction of impactors (3 percent) being smaller, and the rest being larger. About 5 percent of the impactors were considered to be blunt (other tanks). While there is no hard basis for the specific sizes assumed herein, these assumptions are consistent with engineering expectations, and appear to be consistent with real life observations.

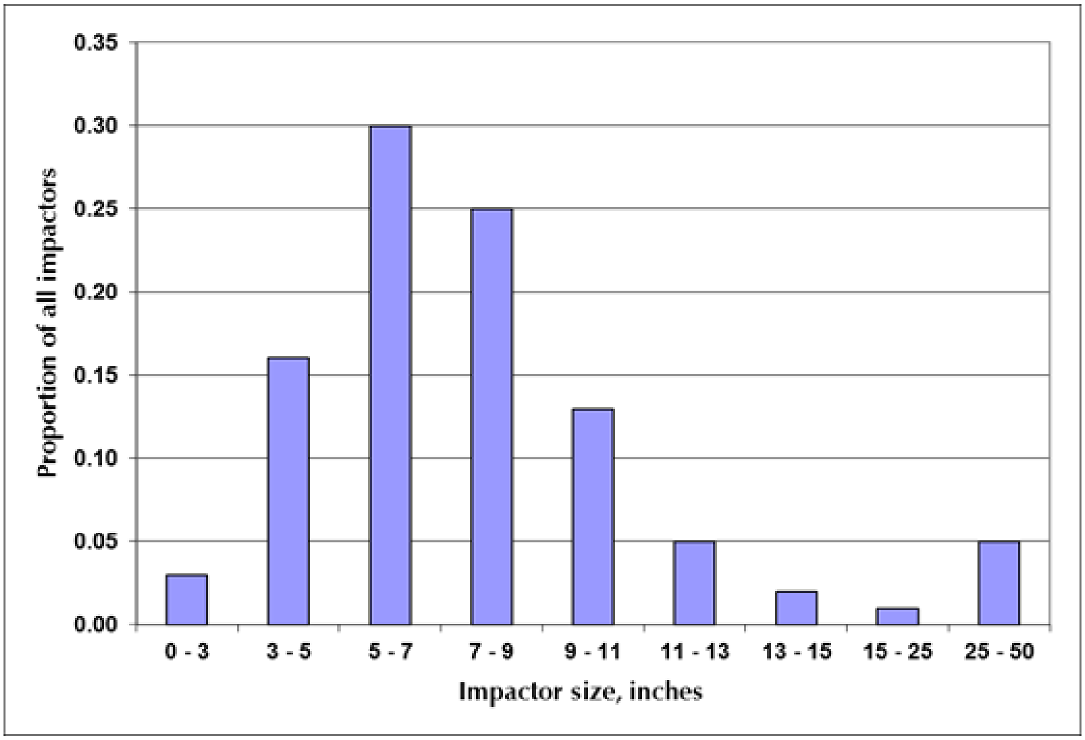

**Figure 6. Assumed Impactor Distribution**

Prior external review of this work suggested that the distribution above might be skewed towards smaller impactors. However, S. Kirkpatrick stated in page 2 of reference [4] that if the combinations of complex impactor shapes (such as couplers and broken rail) and off-axis impactor orientations are considered, many objects will have the puncture potential of an impactor with a characteristic size that is less than 6 inches.

In addition, to ensure that the assumed impactor distribution does not skew the results (i.e., evaluation of relative merits), a sensitivity analysis of the impactor size distribution was conducted. This effort is described in Appendix A, and identified that the **relative performance** of tank car designs or operating conditions was not very sensitive to the impactor distribution assumed, lending additional confidence to the results developed from this effort.

## 3.5 Distribution of Head vs. Shell Impacts

The puncture resistance of tank heads is generally quite different from that of the tank shell, due to differing thickness (presence of head shield) and curvature geometry. Typical tank head strengths have been characterized by the prior FRA work and are represented, in a manner similar to the curves illustrated in Figure 5, by varying slopes of puncture force as a function of impactor size. Knowing how the collisions in a derailment are distributed between head and shell impacts allows the methodology to take the different puncture resistances into account. An analysis of the reported head and shell punctures from 16 hazmat release incidents (2006-2014) indicates that the distribution of impacts between head vs. shell is approximately 50 percent / 50 percent[1].

## 3.6 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. The appropriate car capacity curves (one each for shell and head design) are selected for the car design that is being analyzed. For example, the shell of a base case DOT-111 car is represented by the green line in Figure 5.
2. For each load magnitude (bin) in the load histogram, the impactor size that will result in car puncture is evaluated for every car capacity curve (head and shell).
3. The proportion of impactors that fall below that size threshold, based on the distribution of impactors (Figure 6), represents the probability that a load of that magnitude will result in a car puncture.
4. Probabilities are then weighted by the corresponding prevalence of the impact type (head or shell) and 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 (below) presents the results of such an analysis for two different car designs over two different derailment initiation speeds. The resultant comparisons across designs and across speeds, allows one to evaluate the relative merits of each mitigating strategy. 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 percent better than a base DOT-111 car in a 40 mph derailment. The model also predicts that the same alternate car will be 42 percent more likely to survive if the derailment happened at 30 mph rather than 40 mph.

Results of the analysis for other designs, other speeds, and other braking configurations are presented in Section 5.

**Table 1. Model Estimates for Likely Number of Punctures**

| | | **Most Likely Number of Punctures** | | **% Improvement Compared to Base Case** | | **% Improvement Due to Speed Reduction** |
|---|---|---|---|---|---|---|
| | **Tank Type** | **30 mph** | **40 mph** | **30 mph** | **40 mph** | **40 to 30 mph** |

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[1] FRA derailment data, as received in email from Karl Alexy on 3-Oct-2014.

| | | | | | | |
|---|---|---|---|---|---|---|
| **Base Case** | 7/16" A516-70<br>No Jacket<br>No Head Shield | 8.5 | 13.7 | ~ | ~ | 38% |
| **Alternate** | 9/16" TC128B<br>11 Gauge Jacket<br>1/2” Head Shield | 3.8 | 6.6 | 55% | 52% | 42% |

## 3.7 Summary

In summary, the methodology presented here is used to estimate the relative merits of multiple strategies proposed to improve tank car safety, whether they are in the form of car design improvements or operational restrictions. The next challenge is to verify that the estimates are consistent with expectations from accident histories.

# 4. Validation

Validating a methodology ensures that it generates applicable results. Naturally, the validation process might take different forms depending upon the particular issue that is being studied and the availability of accurate real life or test data against which a validation effort can be initiated.

In this case, a two-step validation effort evaluated whether the estimates and predictions made were consistent with historical data. The first step was to ensure that the dynamic derailment simulations were predicting reasonable and consistent results. The second step was to verify whether the estimates of likely numbers of punctures were consistent with observations.

## 4.1 Dynamic Model Validation

There are no historical records of the force levels associated with tank car punctures under derailment conditions, but data on the number of cars derailed in a given incident are available. Figure 7 compares the number of derailed cars with the train speed for derailment data from the FRA-RAIRS database and the data from the derailment simulations that were generated during this research. According to Figure 7, the simulated predictions of number of cars derailed were consistent with the spread seen in actual derailment data.

Figure 8 presents a similar comparison only using data from recent major tank car derailments (presented in Table 2). Once again, the average of the predictions is in line with the observed data.

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; rather, that they represent a nominal and diverse variety of circumstances, lending credence to the notion that the resulting force histograms are also representative of a ‘nominal’ derailment.

**Table 2. Recent Hazardous Material Derailments**

| Accident | Speed (mph) | Total cars derailed | Total punctures |
|---|---|---|---|
| LaSalle, CO - May, 2014 | 9 | 6 | 0 |
| Lynchburg, VA - May, 2014 | 23 | 17 | 1 |
| Vandergrift, PA - February, 2014 | 30 | 21 | 1 |
| New Augusta, MS - January, 2014 | 45 | 20 | 5 |
| Plaster Rock, NB - January, 2014 | 47 | 19 | 2 |
| Casselton, ND - December, 2013 | 42 | 21 | 20 |
| Aliceville, AL - November, 2013 | 38 | 26 | 25 |
| Lac-Megantic, QC - July, 2013 | 65 | 64 | 59 |

| | | | |
|---|---|---|---|
| Paulsboro, NJ - November, 2012 | 8 | 7 | |
| Plevna, MT - August, 2012 | 25 | 18 | 2 |
| Columbus, OH - July, 2012 | 23 | 17 | 1 |
| Tiskilwa, IL - October, 2011 | 37 | 26 | 5 |
| Arcadia, OH - February, 2011 | 46 | 33 | 29 |
| Windham, CT - March, 2010 | 10 | 4 | 0 |
| Cherry Valley, IL - June, 2009 | 36 | 19 | 13 |
| Luther, OK - August, 2008 | 19 | 14 | 3 |
| Painesville, OH - October, 2007 | 48 | 31 | 1 |
| Oneida, NY - March, 2007 | 47 | 29 | |
| Shepherdsville, KY - January, 2007 | 47 | 26 | |
| Cambria, MN - November, 2006 | 23.5 | 7 | |
| New Brighton, PA - October, 2006 | 37 | 23 | 14 |
| Minot, ND - January, 2002 | 41 | 31 | |

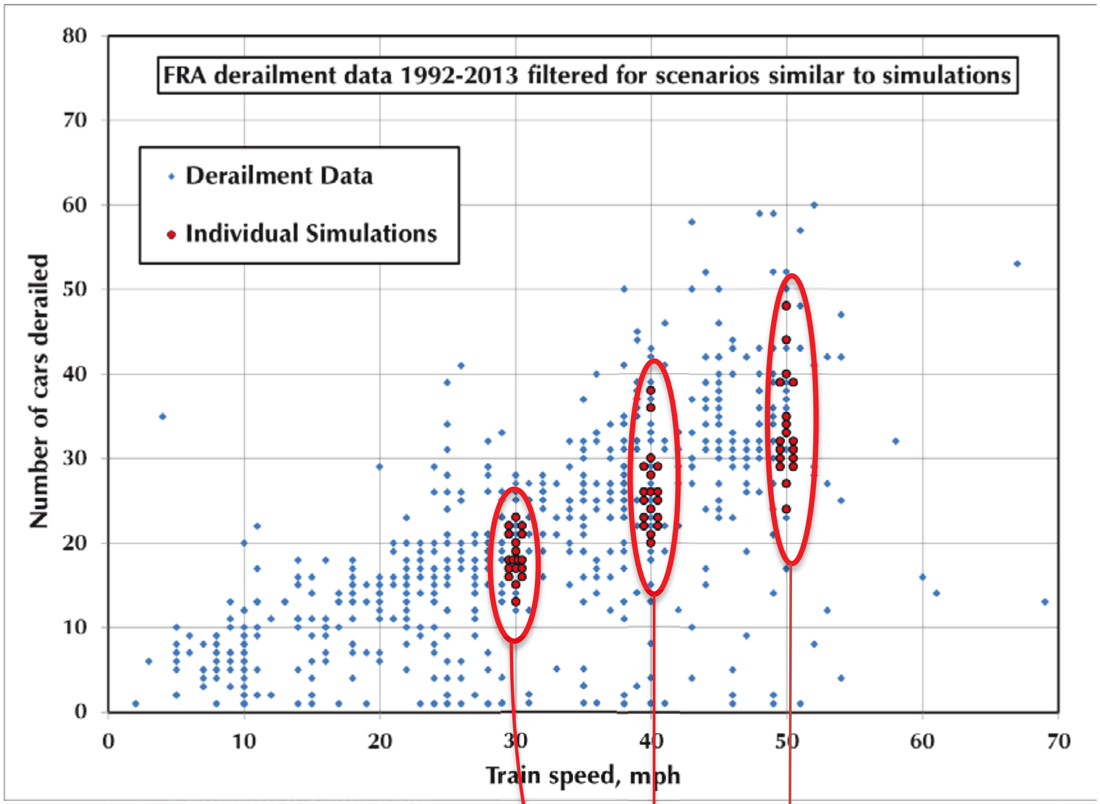

Figure 7. Number of cars derailed vs. Train speed – All derailments

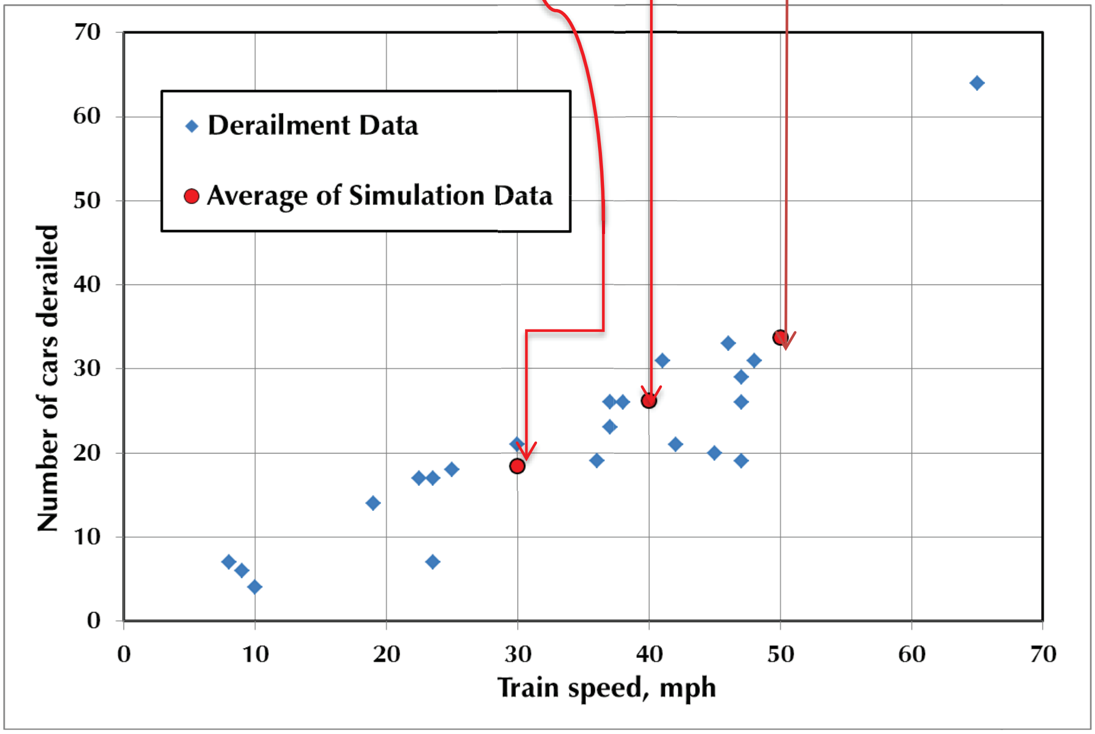

Figure 8. Number of Cars Derailed vs. Train speed – Hazmat Derailments Only (from Table 2)

## 4.2 Validation of Puncture Estimates

The validation described in Section 4.1 lent confidence to the force histogram data extracted from the derailment simulations.  Next, the estimates of likely number of punctures were compared to actual derailment data. Figure 9 compares the model estimates to the number of punctures observed in the various derailments listed in Table 2, including several in which a long string of tank cars, (similar to a unit train) were involved. As expected, the actual derailment data has a wide scatter band (which increases with increasing speed); however, the predictions of the model are well within the cluster of actual values.

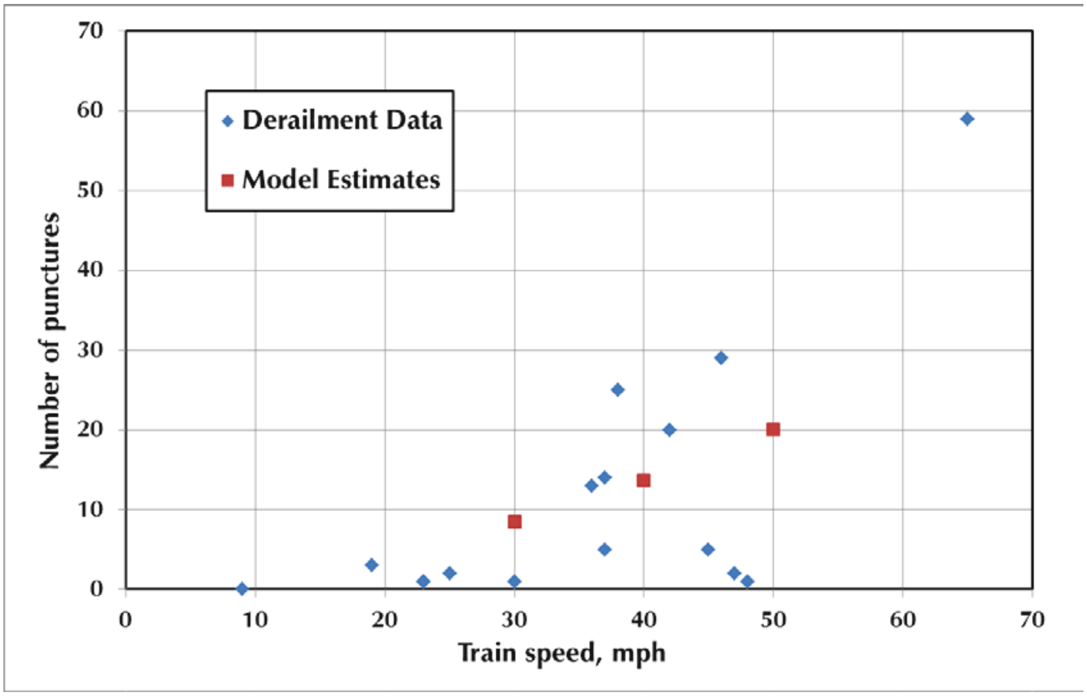

Figure 9. Estimates of Likely Punctures Compared to Derailment Data

## 5. Relative Performance of Mitigating Strategies

Once this objective methodology was established and validated, work continued on extending the effort to evaluate the relative performance of a larger variety of tank designs and train operating conditions. For the 100-car model, a matrix of simulations was established consisting of three initial speeds (30, 40 and 50 mph), four tank designs (base case and three stronger alternatives), and three braking systems (described below). Table 3 shows the most likely number of punctures calculated for each case of this matrix, as applied to a train of 100 cars in which the derailment occurs near the head end.

For each set of simulations, puncture probability was evaluated for the following tank designs, which are based on FRA proposed tank design standards.

- *Base case*: 7/16” thick A516-70 shell, no jacket, no head shield
- *Alternative #1*: 7/16" thick TC128 shell, 11 gauge jacket, 1/2" full-height head shield
- *Alternative #2*: 1/2" thick TC128 shell, 11 gauge jacket, 1/2" full-height head shield
- *Alternative #3*: 9/16" thick TC128 shell, 11 gauge jacket, 1/2" full-height head shield

**Table 3. Most Likely Number of Punctures: 100-Car Train, Derailment at Head End**

| Tank Type | | Speed, mph | Conventional Brakes | 2-way EOT (DP: lead + rear) | ECP Brakes |
|---|---|---|---|---|---|
| **Base Case** | 7/16" A516-70, no jacket, no head shield | 30 | 8.5 | 7.2 | 6.1 |
| | | 40 | 13.7 | 12.1 | 9.8 |
| | | 50 | 20.1 | 16.3 | 14.9 |
| **Alternate 1** | 7/16" TC128, 11 gauge jacket, 1/2" full-height head shield | 30 | 4.7 | 3.9 | 3.3 |
| | | 40 | 8.0 | 7.1 | 5.3 |
| | | 50 | 12.2 | 9.8 | 9.1 |
| **Alternate 2** | 1/2" TC128, 11 gauge jacket, 1/2" full-height head shield | 30 | 4.3 | 3.6 | 2.9 |
| | | 40 | 7.3 | 6.5 | 4.8 |
| | | 50 | 11.2 | 9.0 | 8.3 |
| **Alternate 3** | 9/16" TC128, 11 gauge jacket, 1/2" full-height head shield | 30 | 3.8 | 3.2 | 2.6 |
| | | 40 | 6.6 | 5.9 | 4.3 |
| | | 50 | 10.2 | 8.2 | 7.6 |

In addition to conventional pneumatic braking, derailment simulations were also conducted with alternate braking systems. Electronically Controlled Pneumatic (ECP) braking, where all cars are braked simultaneously, and End-of-Train (EOT) braking, in which the emergency brake signal is initiated simultaneously at both the front and rear of the train, were simulated. EOT braking can be accomplished with either a two-way EOT device or with a remote distributed power (DP) consist at the rear of the train. For the EOT simulations, since the derailment occurred near the front of the train, it was assumed that the lead locomotive immediately transmitted the emergency brake command to the rear of the train. The EOT simulation, in essence, treated the emergency brake signal as initiating from both ends of the train simultaneously and then propagating pneumatically from each end toward the center of the train.

Only considering those scenarios where the derailment occurs near the front of the train overstates the benefit of the EOT and DP brake systems as compared to the benefit of an ECP brake system. If the derailment occurs anywhere in the rear half of the train, the EOT/DP feature offers no advantage over a conventional brake system in a head-end only train. Most derailments result in a 'break-in-two' scenario, where the intact front segment of the train has clearly separated from the derailing rear segment of the train and the front "un-derailed" train segment does not participate in the braking of the rear "derailed" segment. Thus, the brake response of the rear "derailed" segment (the segment that is the focus of this effort) is identical to that of a conventional head-end only train because the entire portion of the train behind the point of derailment (POD) has already begun braking before the emergency signal reaches the head end. If or when the radio brake signal from the rear of the train does reach the head end, any safety benefit imparted to the front "un-derailed" segment is inconsequential to the rear "derailing" segment, as the train has already separated.

If we assume that the POD within the train is equally distributed along the length of the train (as suggested by other reviewers), EOT/DP systems would offer no benefit over conventional head-end-only systems for fully one-half of the derailments, i.e., ones that are initiated in the second half of the train. For the other half of the derailments, the benefits would vary from the predicted peaks benefits if the derailment was initiated at the front end, down to zero benefit if the derailment was initiated at the mid-point. Thus, if one assumes that the POD within the train is equally distributed along the length of the train, the effective benefit of EOT/DP systems would only be one-fourth of the predicted benefit calculated based on head end derailment initiation. Ideally, instead of assuming that the POD is equally distributed, benefit calculations could incorporate observed historical data about the location of derailment initiation to ensure that the benefits offered by advanced braking systems are effectively quantified. Conversely, ECP brakes always offer an advantage (over conventional brakes) regardless of the derailment location in the train, though the magnitude of the performance benefit may vary.

To investigate the effects of various train lengths on the methodology, and recognizing that derailments can initiate anywhere within a train, several sets of simulations (but not the complete matrix) were performed with trains of 80, 50, and 20 cars. Results of these simulations were submitted to DOT. For a given speed, tank design and brake type, shorter trains had fewer punctures. This is expected due to the lower overall kinetic energy in the train behind the POD. The relative benefit, however, of increased tank thickness and/or reduction of train speed is similar to the corresponding benefit seen for the 100-car train with derailment occurring near the front. The risk reduction benefits for alternate braking systems, in contrast, are most pronounced for long trains with many cars behind the POD. Since emergency brake signal propagation is very quick on short trains, especially if initiated at both ends simultaneously, the relative amount of puncture reduction due to the alternate braking systems EOT and ECP is diminished as the number of cars behind the POD decreases.

The effect of the alternate brake systems on the simulated derailment dynamics is displayed in Figure 10. For each combination of speed and brake type, the range of derailed cars (minimum and maximum) over the set of 18 simulations is shown as a vertical bar, and the average value is also indicated. The number of derailed cars generally increases with increasing speed, as expected. At any given speed, ECP braking shows a clear advantage over the other brake systems—both a lower average number of cars derailed and a narrower range, the later possibly due to the reduced slack action associated with ECP braking.

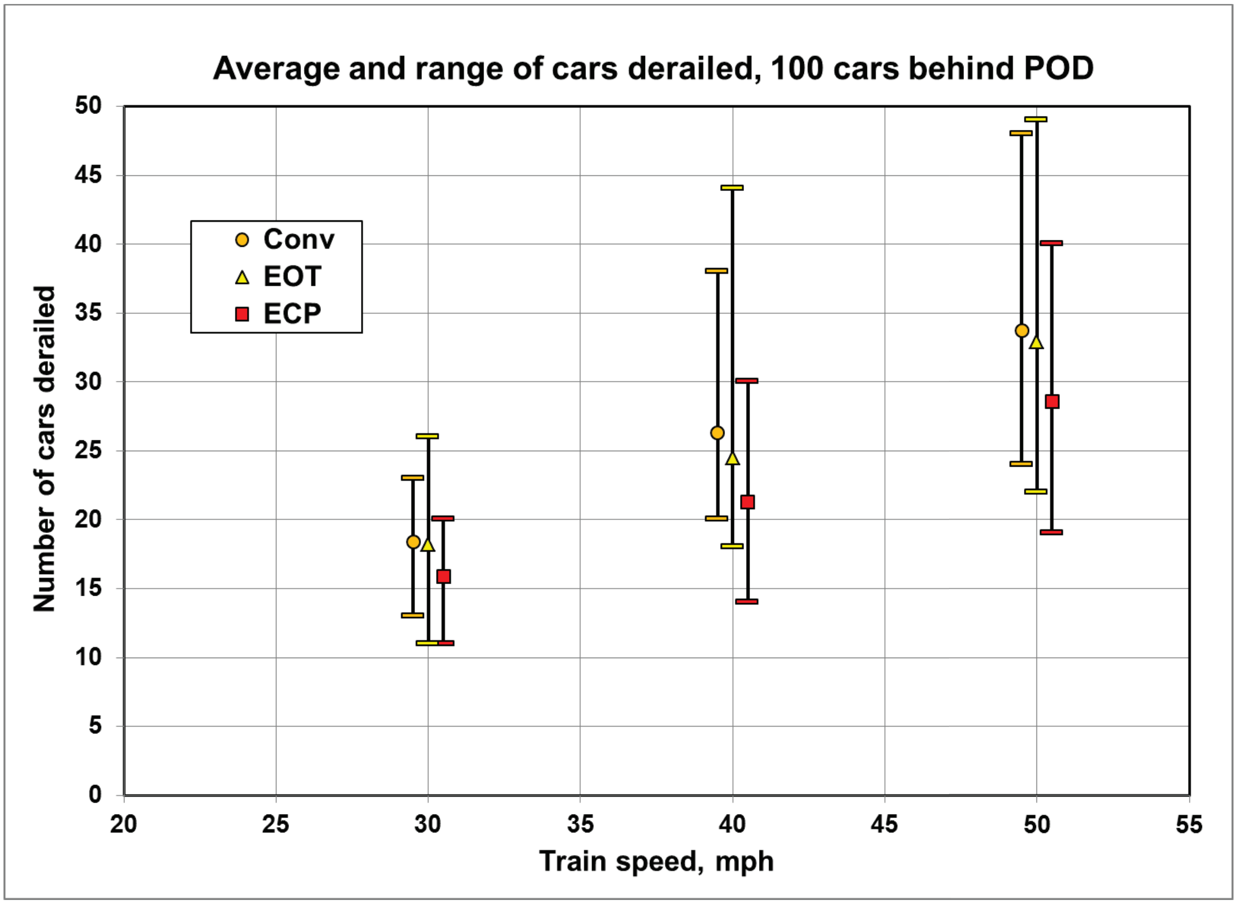

**Figure 10. Average and Range of Cars Derailed for Various Brake Systems**

Table 4 through Table 6 present the estimated risk reduction (percent improvement) associated with various mitigating measures (brake system employed, tank design, and train speed) for a train of 100 cars in which the derailment occurs near the head of the train. Depending on the train speed and tank design used, ECP brakes can be expected to provide about 30 percent reduction in the number of punctures. EOT brakes, at an average of 16 percent reduction, appear to offer about half the benefit of ECP. A tank designed according to the proposed FRA standard (9/16 inch thick TC128 shell with 11 gauge jacket and 1/2 inch full-height head shield) is estimated to cut the puncture risk in half (over 50 percent improvement) compared to the current base case design. The benefit due to speed reduction varies more, but in general, a 10 mph reduction from 50 to 40 mph results in a 34 percent average reduction in punctures, while a 41 percent improvement is expected from 40 to 30 mph. Comparing the 100-car model performance with ECP to its performance without ECP at speeds from 30 to 50 mph, it appears that using

ECP brakes could offer an 8 mph speed advantage; in other words, the risk exposure from derailing with ECP brakes at 40 mph is about the same as derailing with conventional brakes at 32 mph. Similarly, the risk exposure from derailing with ECP brakes at 50 mph is roughly equivalent to derailing with conventional brakes at 42 mph.

**Table 4. Risk Improvement Due to Braking System**

| 100 cars behind POD | | | Most Likely Number of Punctures | | | % Improvement due to brakes only | | |
|---|---|---|---|---|---|---|---|---|
| | Tank Type | Speed, mph | Conventional Brakes | 2-way EOT (DP: lead + rear) | ECP Brakes | Conventional Brakes | 2-way EOT (DP: lead + rear) | ECP Brakes |
| Base Case | 7/16" A516-70, no jacket, no head shield | 30 | 8.5 | 7.2 | 6.1 | 0% | 15% | 28% |
| | | 40 | 13.7 | 12.1 | 9.8 | 0% | 12% | 28% |
| | | 50 | 20.1 | 16.3 | 14.9 | 0% | 19% | 26% |
| Alternate 1 | 7/16" TC128, 11 gauge jacket, 1/2" full-height head shield | 30 | 4.7 | 3.9 | 3.3 | 0% | 17% | 30% |
| | | 40 | 8.0 | 7.1 | 5.3 | 0% | 11% | 34% |
| | | 50 | 12.2 | 9.8 | 9.1 | 0% | 20% | 25% |
| Alternate 2 | 1/2" TC128, 11 gauge jacket, 1/2" full-height head shield | 30 | 4.3 | 3.6 | 2.9 | 0% | 16% | 33% |
| | | 40 | 7.3 | 6.5 | 4.8 | 0% | 11% | 34% |
| | | 50 | 11.2 | 9.0 | 8.3 | 0% | 20% | 26% |
| Alternate 3 | 9/16" TC128, 11 gauge jacket, 1/2" full-height head shield | 30 | 3.8 | 3.2 | 2.6 | 0% | 16% | 32% |
| | | 40 | 6.6 | 5.9 | 4.3 | 0% | 11% | 35% |
| | | 50 | 10.2 | 8.2 | 7.6 | 0% | 20% | 25% |
| | | | | | | **Average:** | **16%** | **30%** |

## Table 5. Risk Improvement Due to Tank Construction

| **100 cars behind POD** | | | **Most Likely Number of Punctures** | | | **% Improvement due to tank construction only** | | |
|---|---|---|---|---|---|---|---|---|
| | **Tank Type** | **Speed, mph** | **Conventional Brakes** | **2-way EOT (DP: lead + rear)** | **ECP Brakes** | **Conventional Brakes** | **2-way EOT (DP: lead + rear)** | **ECP Brakes** |
| Base Case | 7/16" A516-70, no jacket, no head shield | 30 | 8.5 | 7.2 | 6.1 | 0% | 0% | 0% |
| | | 40 | 13.7 | 12.1 | 9.8 | 0% | 0% | 0% |
| | | 50 | 20.1 | 16.3 | 14.9 | 0% | 0% | 0% |
| Alternate 1 | 7/16" TC128, 11 gauge jacket, 1/2" full-height head shield | 30 | 4.7 | 3.9 | 3.3 | 45% | 46% | 46% |
| | | 40 | 8.0 | 7.1 | 5.3 | 42% | 41% | 46% |
| | | 50 | 12.2 | 9.8 | 9.1 | 39% | 40% | 39% |
| Alternate 2 | 1/2" TC128, 11 gauge jacket, 1/2" full-height head shield | 30 | 4.3 | 3.6 | 2.9 | 49% | 50% | 52% |
| | | 40 | 7.3 | 6.5 | 4.8 | 47% | 46% | 51% |
| | | 50 | 11.2 | 9.0 | 8.3 | 44% | 45% | 44% |
| Alternate 3 | 9/16" TC128, 11 gauge jacket, 1/2" full-height head shield | 30 | 3.8 | 3.2 | 2.6 | 55% | 56% | 57% |
| | | 40 | 6.6 | 5.9 | 4.3 | 52% | 51% | 56% |
| | | 50 | 10.2 | 8.2 | 7.6 | 49% | 50% | 49% |
| | | | | | | **Average:** | **53%** | |

## Table 6. Risk Improvement Due to Speed Reduction

| **100 cars behind POD** | | | **Most Likely Number of Punctures** | | | **% Improvement due to 10 mph speed reduction only (50 to 40 mph, and 40 to 30 mph)** | | | **Speed (mph) advantage: amount that conventionally braked train must reduce speed to obtain equivalent risk** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Tank Type** | **Speed, mph** | **Conventional Brakes** | **2-way EOT (DP: lead + rear)** | **ECP Brakes** | **Conventional Brakes** | **2-way EOT (DP: lead + rear)** | **ECP Brakes** | **Conventional Brakes** | **2-way EOT (DP: lead + rear)** | **ECP Brakes** |
| Base Case | 7/16" A516-70, no jacket, no head shield | 30 | 8.5 | 7.2 | 6.1 | 38% | 40% | 38% | --- | --- | --- |
| | | 40 | 13.7 | 12.1 | 9.8 | 32% | 26% | 34% | 0.0 | 3.1 | 7.5 |
| | | 50 | 20.1 | 16.3 | 14.9 | --- | --- | --- | 0.0 | 5.9 | 8.1 |
| Alternate 1 | 7/16" TC128, 11 gauge jacket, 1/2" full-height head shield | 30 | 4.7 | 3.9 | 3.3 | 41% | 45% | 38% | --- | --- | --- |
| | | 40 | 8.0 | 7.1 | 5.3 | 34% | 28% | 42% | 0.0 | 2.7 | 8.2 |
| | | 50 | 12.2 | 9.8 | 9.1 | --- | --- | --- | 0.0 | 5.7 | 7.4 |
| Alternate 2 | 1/2" TC128, 11 gauge jacket, 1/2" full-height head shield | 30 | 4.3 | 3.6 | 2.9 | 41% | 45% | 40% | --- | --- | --- |
| | | 40 | 7.3 | 6.5 | 4.8 | 35% | 28% | 42% | 0.0 | 2.7 | 8.3 |
| | | 50 | 11.2 | 9.0 | 8.3 | --- | --- | --- | 0.0 | 5.6 | 7.4 |
| Alternate 3 | 9/16" TC128, 11 gauge jacket, 1/2" full-height head shield | 30 | 3.8 | 3.2 | 2.6 | 42% | 46% | 40% | --- | --- | --- |
| | | 40 | 6.6 | 5.9 | 4.3 | 35% | 28% | 43% | 0.0 | 2.5 | 8.2 |
| | | 50 | 10.2 | 8.2 | 7.6 | --- | --- | --- | 0.0 | 5.6 | 7.2 |
| | | | | | | **Average, 40 to 30 mph** | **41%** | | **Average:** | **4.2** | **7.8** |
| | | | | | | **Average, 50 to 40 mph** | **34%** | | | | |

## 6. Conclusion

The methodology developed in this report allows railroad and tank car industry  to estimate the relative performance benefits of changes in tank car designs, braking systems, or operating conditions under derailment conditions, with a focus on the likelihood of a tank to puncture (and thus release hazardous materials). The results presented in this report included the expected relative performance of several proposed tank car designs (compared to a legacy DOT-111 car), the benefits of advanced braking systems (such as ECP brakes) over conventional systems, and the safety performance of lower operating speeds.

The methodology captured several elements/parameters relevant to derailment and puncture performance, as well as its distributions, and combined them into a consistent probabilistic framework for estimating the relative merit of proposed mitigation strategies that aim to tank car puncture performance. When the estimates generated by this methodology were compared to actual derailment data, the methodology properly captured the gross dynamics of a tank car train derailment and the resulting puncture performance of the tank cars. 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. Also, puncture risk reduction correlated well with engineering estimates corresponding to increased tank shell thickness and material strength. The validation effort provided confidence that the approach not only captured relative merits, but also that the overall puncture probability predictions resulting from this approach were consistent with observed derailment performance.

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

# 7. References

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# Appendix A.
# Study of Impactor Distributions

This research effort aimed to develop and validate a methodology that could be used to estimate the relative merit of proposed mitigation strategies to improve tank car puncture performance. One of the key elements and assumptions of this methodology was the distribution of impactor sizes, as this had the potential to significantly influence the results.

To evaluate the sensitivity of the results to variations in impactor size distribution, two additional sets of impactor distributions, one skewed towards smaller impactor sizes and one skewed towards larger impactor sizes (compared to the standard distribution assumed, shown in figure 6) were also analyzed. Figure A1 displays the two distributions compared to the standard one used for the main analyses. The average impactor sizes for the three distributions are about 6.8”, 8.7”, and 11.3”, respectively, with the geometric mean of the averages of smaller and larger distributions being equal to the average of standard distribution. The standard distribution has an average size that is about 29 percent bigger than the smaller one and the larger distribution is about 29 percent bigger than the standard one.

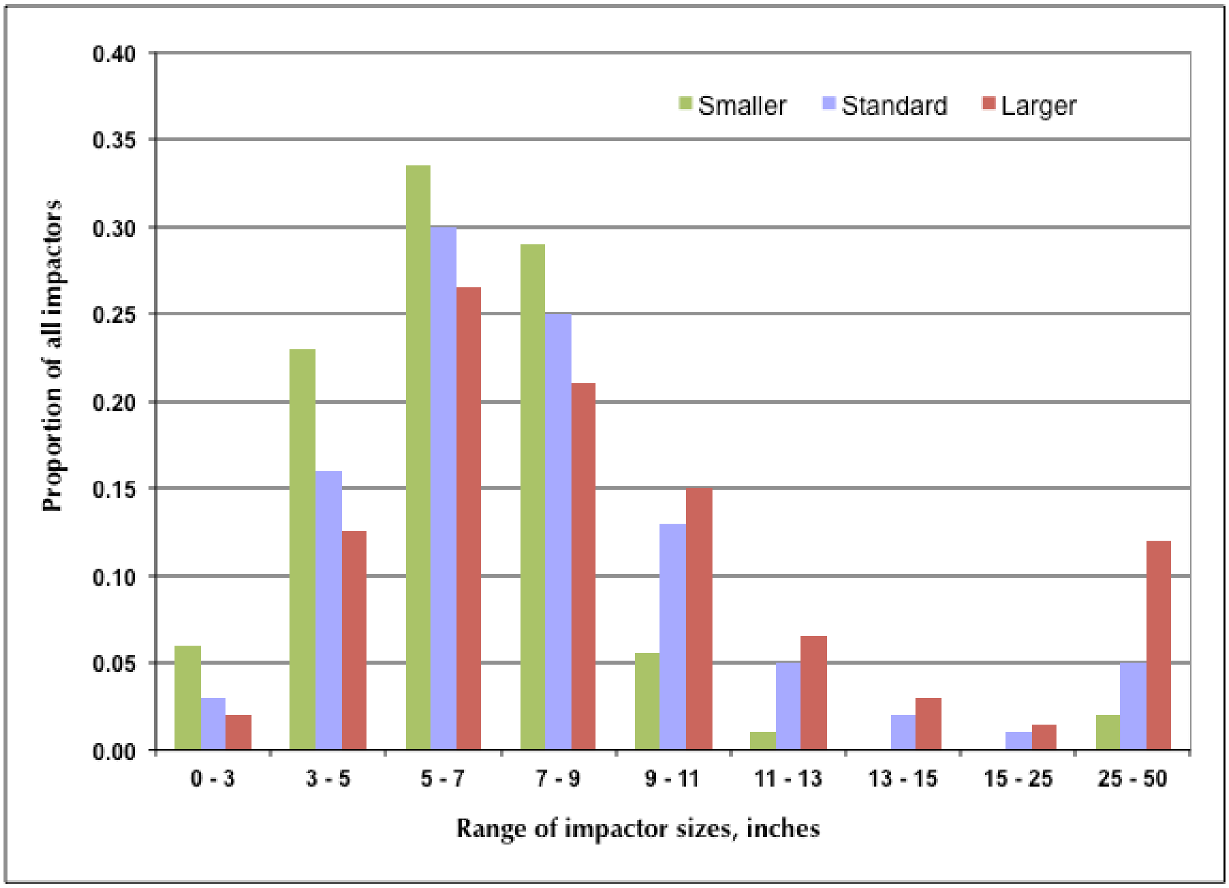

**Figure A1. Impactor distributions used for sensitivity analysis**

The results of this evaluation are presented in Tables A.1, A.2 and A.3 below. Table A.1 shows the puncture performance of two different designs and two different brake systems for a 100-car train and a derailment initiation speed of 40 mph. As expected, smaller impactors result in more punctures and larger impactors result in fewer punctures. However, as seen in Tables A.2 and A.3, the variation in relative performance values is far less significant, especially considering that the impactor distributions are significantly different.

**Table A.1 Number of Punctures – Variations by Impactor Size Distribution**

| **40 mph, 100 cars > POD** | | | **Most Likely Number of Punctures** | | |
|---|---|---|---|---|---|
| | **Tank Type** | **Brakes** | **Smaller size impactors** | **Standard impactor distribution** | **Larger size impactors** |
| Base Case | 7/16" A516-70, No Jacket | Conv | 15.1 | 13.0 | 11.4 |
| | | ECP | 11.0 | 9.3 | 8.0 |
| Alternate 3 | 9/16" TC128, 11 gauge Jacket | Conv | 10.4 | 8.5 | 7.2 |
| | | ECP | 7.1 | 5.6 | 4.7 |

**Table A.2 Relative Performance of ECP Brakes – Variations by Impactor Size Distribution**

| **40 mph, 100 cars behind POD** | | **% Improvement<br>ECP compared to Conventional Brakes** | | |
|---|---|---|---|---|
| | **Tank Type** | **Smaller size impactors** | **Standard impactor distribution** | **Larger size impactors** |
| Base Case | 7/16" A516-70, No Jacket | 27% | 28eirth | 30% |
| Alternate 3 | 9/16" TC128, 11 gauge Jacket | 32% | 34% | 35% |

**Table A.3 Relative Performance of Tank Designs – Variations by Impactor Size Distribution**

| **40 mph, 100 cars behind POD** | **% Improvement<br>9/16" shell compared to 7/16" shell** | | |
|---|---|---|---|
| **Brake System** | **Smaller size impactors** | **Standard impactor distribution** | **Larger size impactors** |
| Conventional | 31% | 35% | 37% |
| ECP | 35% | 40% | 41% |

Again, the tables presented show that the relative performance of changes to tank car designs or operating conditions does not change significantly as a result of changes to the impactor size distribution. While the individual puncture values change notably (as they should), relative performance does not. It is also worth mentioning that the standard impactor size distribution assumed herein results in puncture values that are consistent with real-life observations, lending additional credence to using it for the main work reported here.

## Abbreviations and Acronyms

| | |
|---|---|
| DP | Distributed Power |
| ECP | Electronically Controlled Pneumatic |
| EOT | End-of-Train |
| POD | Point of Derailment |
| NBR | Net Braking Ratio |
| 2-EOT | Two Way End-of-Train |