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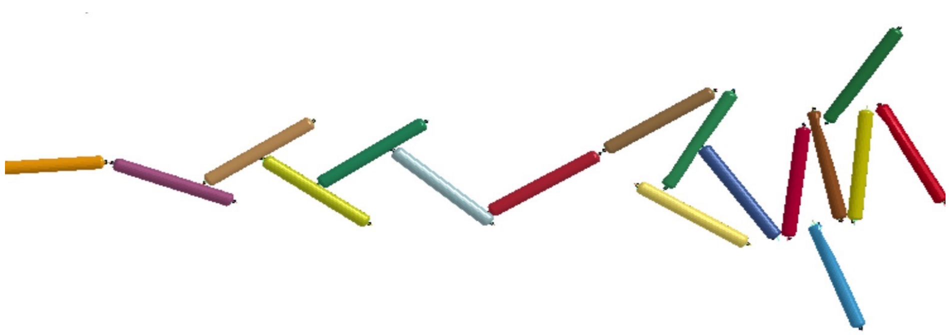
LETTER REPORT

EVALUATION OF RISK REDUCTION FROM LNG TANK CAR DESIGN IMPROVEMENTS



U.S. Department of Transportation
Federal Railroad Administration

OFFICE OF RESEARCH & DEVELOPMENT

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EXECUTIVE SUMMARY

The United States Department Of Transportation (USDOT) is currently engaged in rule-making efforts to authorize the transportation of Liquefied Natural Gas (LNG) by Rail, if the safety and requirements outlined in the rule are followed.

USDOT is considering DOT-113 specification cryogenic tank cars, as well as, other alternatives with even thicker outer shells as potential vehicles for the transportation of LNG. This work evaluated the relative risk of tank puncture (leading to loss of LNG lading) in a unit train of DOT-113 specification cryogenic tank cars as well as an alternate design with a thicker outer shell, operating at different speeds. The puncture risk of two different tank wall thicknesses was then compared.

Prior work had developed and validated a methodology to estimate the relative safety benefits (i.e., risk reduction) resulting from changes in tank car design or operating conditions, focusing on the likelihood of a tank to puncture (and thus release hazardous materials), following a derailment. 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.

The base tank car considered in this analysis is based on a typical DOT-113 cryogenic tank car design, consisting of a 7/16” steel outer tank enclosing a 1/4” stainless steel inner tank. The annular space between these tanks is evacuated and insulated.

Trains composed of 100 loaded LNG tank cars were simulated to derail from initial speeds of 30, 40, and 50 mph. In order to derive a nominal force spectrum that reasonably represents typical variations in conditions and circumstances, a set of 18 different simulations were performed at each speed. Parameters representing friction between tank cars and ground, lateral track stiffness, and lateral derailment initiating force were varied to obtain the 18 different scenarios.

Two different tank designs were evaluated using the collision impact force results from the derailment simulations:

- Base: 7/16” thick steel shell with 1/2” thick heads and 1/4” stainless steel inner tank
- Alternate: 9/16” thick steel shell with 5/8” thick heads and 1/4” stainless steel inner tank

For the base car at a 40 mph derailment speed, the expected number of punctures is 5. It is estimated that 20% of the punctures could happen on the same car. In other words, since the expected number of punctures for 7/16” shell at 40 mph is 5, the expected number of cars punctured for this scenario is 4.

The model predicted that the alternate tank design, with a 9/16” shell, would perform 16% better, in a 40 mph derailment, than the car with a 7/16” shell. The model also predicts that for the same alternate car, the risk of puncture will be 50% less if the derailment happened at 30 mph rather than 40 mph.

Evaluation of Risk Reduction from LNG Tank Car Design Improvements

1. Background

The Pipeline and Hazardous Materials Safety Administration (PHSMA) has issued a special permit (No. DOT-SP 20534) to Energy Transport Solutions, LLC (ETS), which authorizes shipments of LNG by rail in unit-train configurations (e.g., 100-car consist) between Wyalusing, Pennsylvania and Gibbstown, New Jersey, with no intermediate stops. The DOT is currently engaged in rule-making efforts to extend the special permit into a full rule that authorizes transportation of LNG by Rail, if the safety and requirements outlined in the rule are followed. The DOT is considering DOT-113 specification cryogenic tank cars, as well as, other alternatives with even thicker outer shells as potential vehicles for the transportation of LNG.

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. 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.

The Federal Railroad Administration (FRA) contracted Sharma and Associates and in prior work, reported in two letter reports [1, 2] and other publications [3-6], 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. Further validation of the methodology is described in publications [7,8].

This work evaluated the relative risk of tank puncture (leading to loss of LNG lading) in a unit train of DOT-113 specification cryogenic tank cars operating at different speeds. The puncture risk of two different tank wall thicknesses was also compared.

2. Overview of Methodology

The likelihood of a given tank car puncture during a derailment is affected by several variables and circumstances, among which are:

- **The derailment scenario**, including the speed at 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 result in 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 (or weaker) the tank shell, the higher the probability of puncture.

The approach taken here considers the above parameters and circumstances to evaluate the probability, or likelihood, that a certain number of punctures may be experienced by tanks of a given design, during a derailment event. Further, rather than focusing on specific values of the above parameters, the 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. A conceptual overview of this approach is presented in Figure 1.

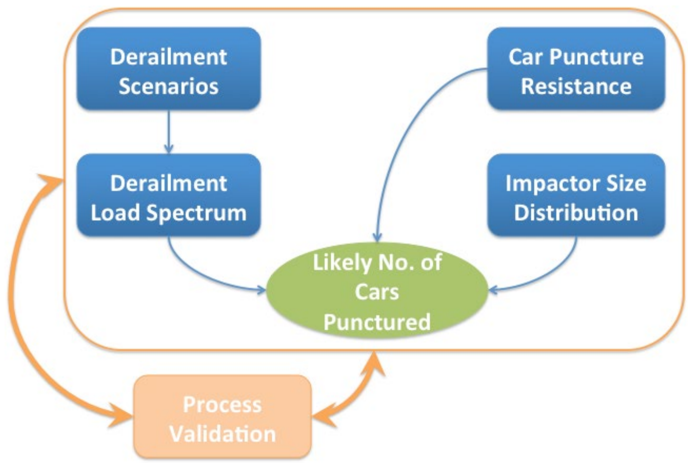

Figure 1. Overall concept of approach

The methodology is executed through the following steps:

- Conduct a set of 18 derailment simulations for each initial train speed (train length and location of the Point Of Derailment (POD) were held constant in this analysis). The 18 simulations were based on the following variable combinations:
  - o Three values of coefficient of friction between tank cars and ground, representing 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. 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.
  - o Three values of lateral force to initiate derailment: 50, 70, and 90 kips. These values represent a truck side lateral/vertical (L/V) force 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.
  - o Two values of lateral track stiffness, representing variations in track quality: 30 and 40 kips/in, were considered; the 40 kips/in value would represent a truck side L/V ratio of 0.6

at 1 inch of lateral wheel movement, with the 30 kip/in value representing poorer quality track that was 25% more flexible.

- Accumulate the collision forces from all cars in the train, over all 18 simulations in the set, into a histogram of collision forces, with the number of collisions in each bin being normalized over the set of 18 simulations. The resulting histogram indicates the number of collisions, at each force level, for a nominal derailment under the subject conditions.
- Characterize the design strength of a given car design as a function of impactor size (based on prior work)
- Based on an expected impactor size distribution, the collision force histogram, and the car strength, calculate the expected number of punctures

By comparing the expected number of punctures across multiple tank designs and multiple train speeds at derailment, the relative risk can be estimated.

3. Validation of Methodology

Prior validation work [1-8] has shown 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. In particular, the validation efforts described in publication [7] presented additional elements supporting model confidence in the DOT methodology, including:

- Confidence in the input parameters
- Confirmation that the trends of model prediction are in line with expectations
- Validation against physical derailment data
- Comparison with other studies

These reported efforts further confirm the DOT's confidence that its 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 confidence comes not just from one point of validation, but also from a review of several elements of both inputs to and outputs from the model [8].

4. Modeling the Derailment Scenarios

The base tank car modeled in this analysis is based on a typical DOT-113 cryogenic tank car design, as proposed for hauling LNG. The cryogenic design consists of a 7/16" steel outer tank enclosing a 1/4" stainless steel inner tank. The annular space between these tanks is evacuated and insulated.

The weight of the LNG lading is accounted for by increasing the density of a secondary outer layer with low stiffness. Thus, the mass of the car is increased without affecting the strength of the outer tank. Point masses representing the trucks are added to the outer tank at the center plate locations. Total loaded car weight is 267,500 pounds. The overall length of the modeled tank car is 81'10". The same draft gear and coupler joint connections used in previous work for simulating crude oil cars [2] have been used in this model as well. The simulated trains were composed of 100 loaded tank cars. The 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.

As in the previous work [2], the following assumptions were made:

- The cars were individually modeled in three dimensions (3-D), 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”, 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”, the truck was considered to have derailed and the center plate was subsequently free to move laterally.

- The cars were connected with discrete draft gear and coupler models. The coupler models allowed a 7^{o} swing in each direction, with the knuckles modeled to resist rotation and fail when the rotation exceeds 13.5^{o}, which is consistent with the coupler rotation limits defined for E-type couplers in the AAR Manual [9].

- The tanks were free to move in any direction, while the bolsters were constrained to move in a horizontal plane; i.e., the tanks were allowed to slide and rotate, but not roll over or ride up on top of one another.

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 was imparted to all the cars. Emergency braking was initiated at the head end to simulate a derailment and train separation just behind the lead consist. The emergency brake application was also initiated at the rear of the train, after an appropriate transmission delay, to simulate the action of a remote distributed power (DP) unit or a 2-way end-of-train (EOT) device.

Based on field observations and brake rack testing [7], a front to rear transmission delay of 2.0 seconds was used in the simulations. Also in this testing, a 0.17 second delay was observed between the moment of hose separation and the initiation of cylinder pressure build-up on the car adjacent to the hose break at the point of derailment. Since only the portion of the train behind the break-in-two is simulated, this means that the brake cylinder pressure on the first simulated car begins to build up at 0.17 seconds after the start of the simulation. Initiation of cylinder pressure build-up on subsequent cars is based on the measured emergency pneumatic propagation rate and the brake pipe length of the modeled LNG tank car. The pneumatic signal propagation is modeled as a 94 msec interval between initiation of brake cylinder pressure build-up on adjacent cars. The retarding force applied is 13,255 pounds per car which represents an emergency associated with a 12% Net Braking Ratio (NBR). Brake cylinder pressure build-up curves were modeled based on measured time history profiles [7].

In order to derive a 'nominal' force spectrum from the simulation of a set of derailments that reasonably represent typical variations in conditions and circumstances, a series of simulations varying the following parameters were run:

- Three initial train speeds: 30, 40 and 50 mph.
- Three values of coefficient of friction between tank cars and ground, representing multiple terrain conditions: 0.27, 0.30, and 0.33.
- Three values of lateral force to initiate derailment: 50, 70 and 90 kips.
- Two values of lateral track stiffness, representing variations in track quality: 30 and 40 kips/inch.

5. Impact Load Spectrum

The 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 2 presents the final pile-up images for each of the 18 runs for the derailment initiation speed of 40 mph. As evident from these images, this set of runs reflects a reasonable breadth of derailment scenarios, supporting the contention that this methodology generates a 'nominal' force histogram associated with a 'nominal' derailment.

The collision impact forces between tank cars 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 3 presents these 'nominal' force histograms. 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 higher consequence).

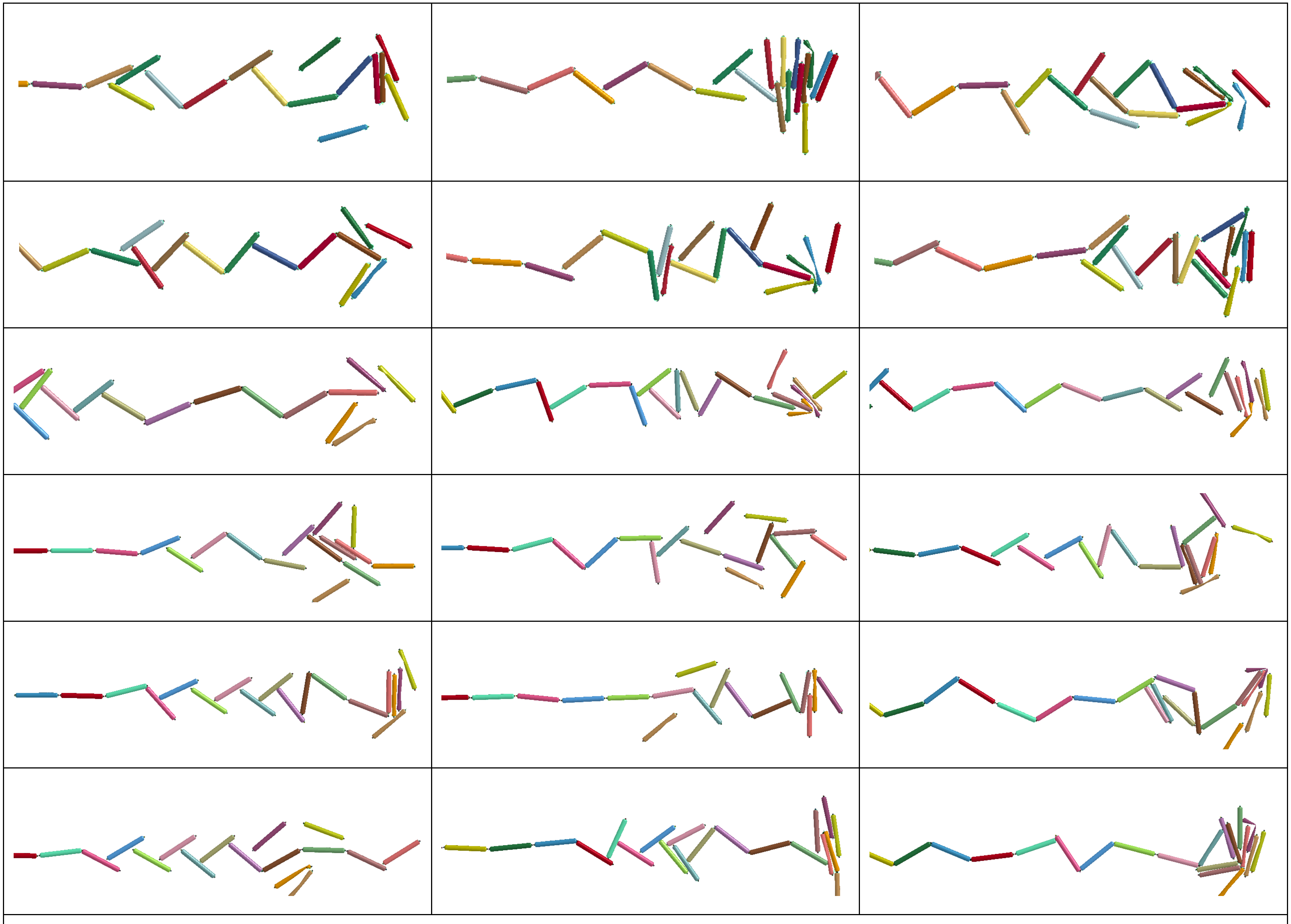

Figure 2. Distribution of derailments - Final pile-ups from 18 scenarios at 40 mph

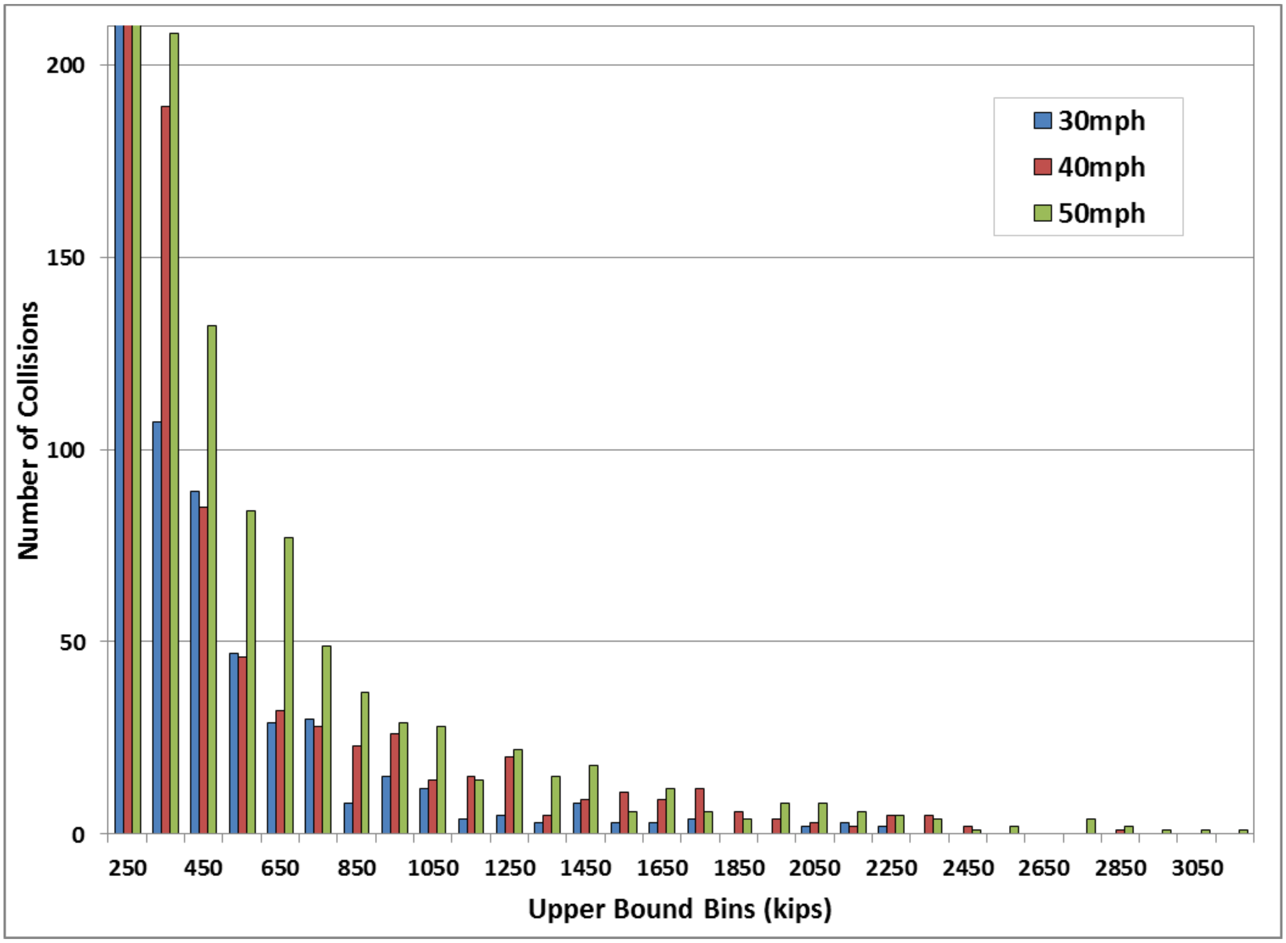

Figure 3. Histograms of collision forces at 30, 40, and 50 mph

6. Tank Car Puncture Resistance

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, 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 [10]. Such charts were developed to characterize the puncture resistance of different tank car designs, ranging from DOT111 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, which is the square root of the area of the impactor face, is used to define these impactor sizes.

For a DOT111 tank car (7/16” A-516-70 tank shell, no jacket), represented by the green line in Figure 4, a 3” impactor will puncture the tank at a little over 200,000 lb. A 6” impactor would not puncture the tank until the force levels approach 400,000 lb. Essentially, the chart defines the force level at which a given impactor would puncture the tank shell of a particular design (thickness and material). Alternately said, the chart defines the impactor size that would result in tank puncture for a given puncture force level.

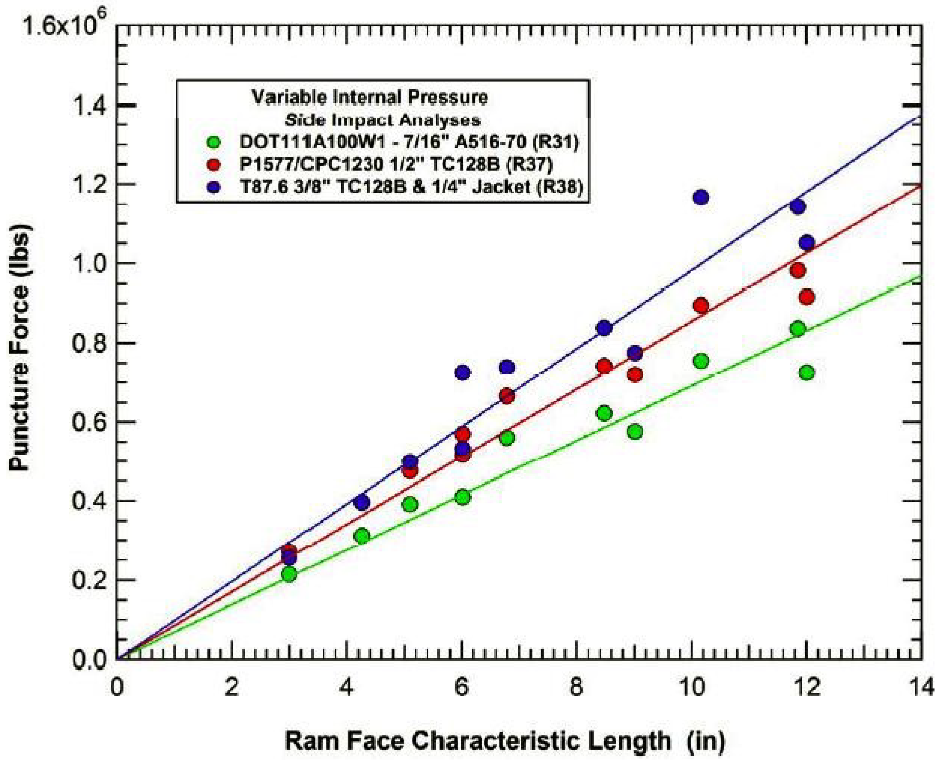

Figure 4. Capacity of tank car shell to withstand impact

Tanks with greater puncture resistance, those composed of thicker and/or stronger material, are represented in Figure 4 by lines with higher slope. For example, a tank with 1/2" shell made of TC128 (red line) has greater puncture resistance than one made with 7/16" thick A-516-70 steel (green line).

Figure 5 [10] shows a linear approximation of puncture force data that has been normalized to the sum of the thicknesses of the tank components (tank shell and jacket, for these data). Since this relationship is based on combined data for various materials, the slope of this line, which is 0.16 million pounds / inch of material / inch of impactor size, characterizes the shell puncture resistance for various tank car construction designs. So, for the double-walled construction of the LNG tank car, this slope was used along with the sum of the inner and outer tank shell thicknesses (0.6875 inches) to characterize the puncture resistance of the LNG tank shell.

This impact resistance was further compared to test results from an impact tests of a DOT 113 car [12] and a DOT 117 car [13] that were conducted by FRA. The comparison to a DOT 117 car is relevant because the total thickness of a DOT 117 car (9/16th inch outer shell with a 1/8th inch jacket) is very similar to the DOT 113. Based on references [12, 13], under test conditions, it appears that the puncture energy of the DOT113 tank is about 2.1 Million ft-lbs, while the puncture energy of the DOT-

117 is about 2 Million ft-lbs. Comparing the energy capacities of the two tank designs (DOT113 at 2.1 M ft-lbs, and the DOT117 at 2 M ft-lbs), suggests that their performances are very similar, and that the DOT113 might even have a slightly better performance. Therefore, the impact resistance that we have assumed in our analysis should be reasonable, if not slightly conservative.

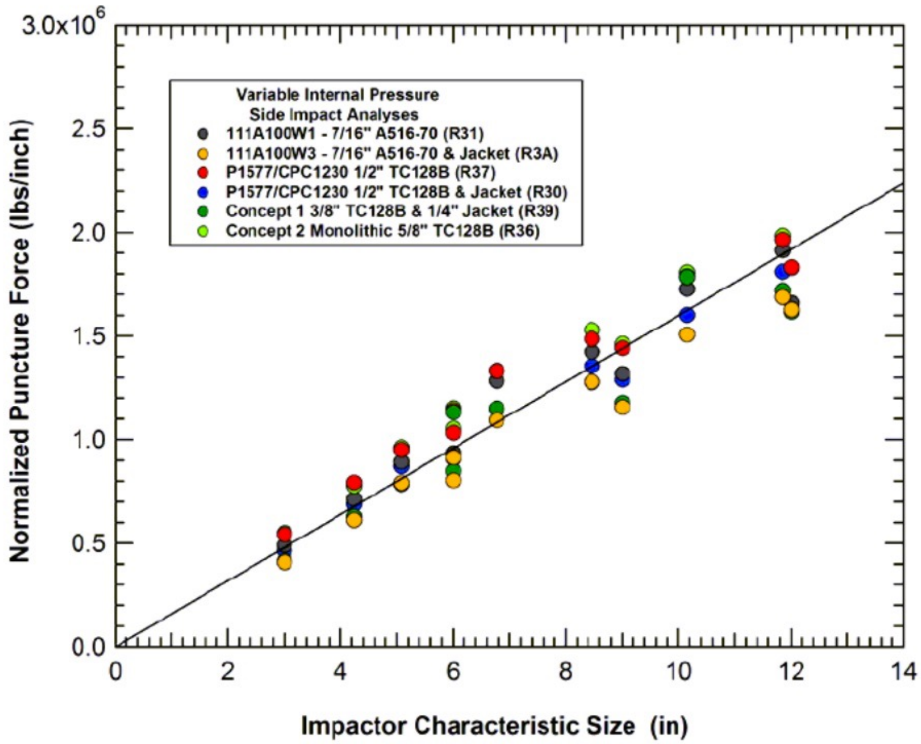

Figure 5. Normalized puncture force vs. impactor size for various tank shell designs

Tank heads have a slightly different puncture resistance, which is discussed in the next section of this report.

7. 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 prior FRA work [11] and are represented, in Figure 6, as puncture force data as a function of overall thickness for a 6”x6” impactor. This relationship has been generalized for other impactor sizes in a manner similar to shell impacts (Figure 5), resulting in a head impact puncture resistance characterization of 0.14 million pounds / inch of material / inch of impactor size. The overall head thickness for the LNG tank is 0.75 inches, consisting of a 1/2” outer tank head and the 1/4” inner tank.

Knowing how the collisions in a derailment are distributed between head and shell impacts allows the methodology to take their differing puncture resistances into account. An analysis of the reported head and shell punctures from hazmat release incidents involving tank cars carrying crude oil or ethanol indicates that the distribution of impacts between head vs. shell is approximately 50% / 50% [2]. The LNG tank cars are substantially longer (by 30% to 40%) than typical crude oil or ethanol cars, and hence their shell area is relatively more exposed than their heads. For this analysis, it was assumed that the distribution of shell to head impacts was 67% shell and 33% head.

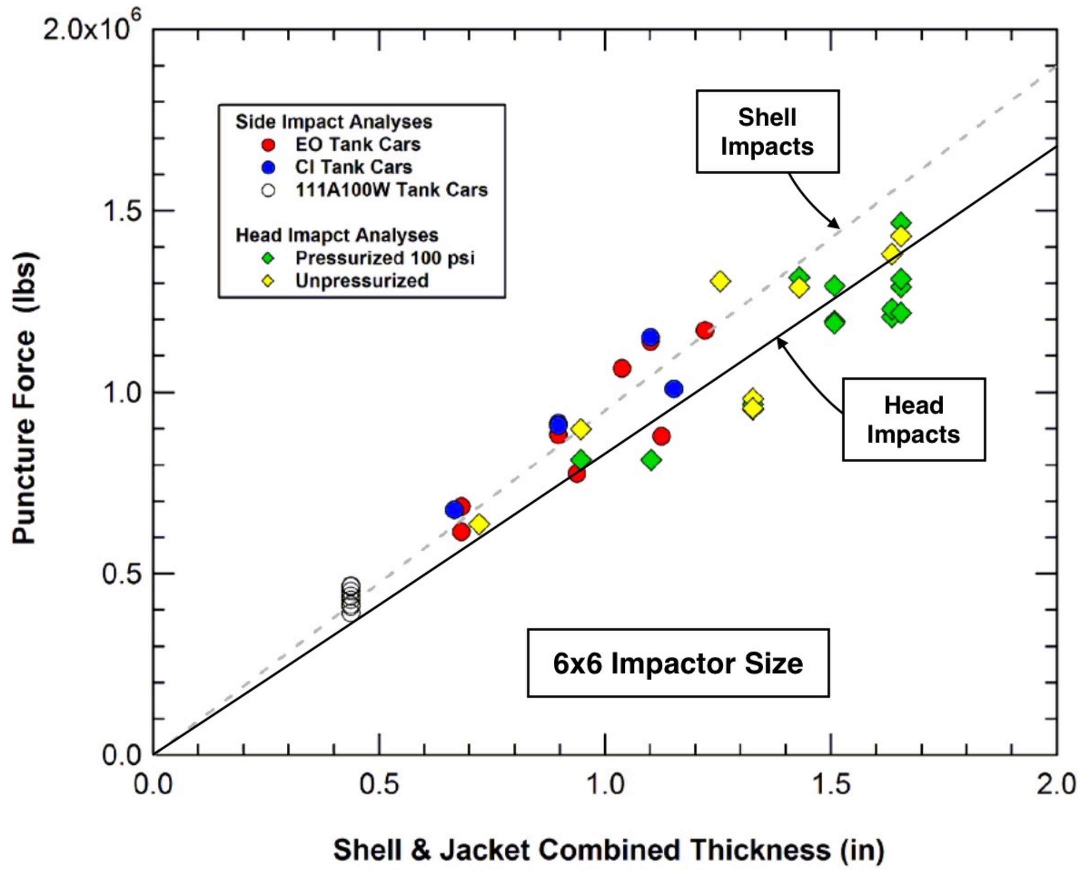

Figure 6. Puncture force vs. overall tank thickness for 6" impactor

8. Impactor Distribution

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" to more than 12". 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. This analysis uses the same impactor distribution, shown in Figure 7, which has been used in prior FRA work [2,7,8].

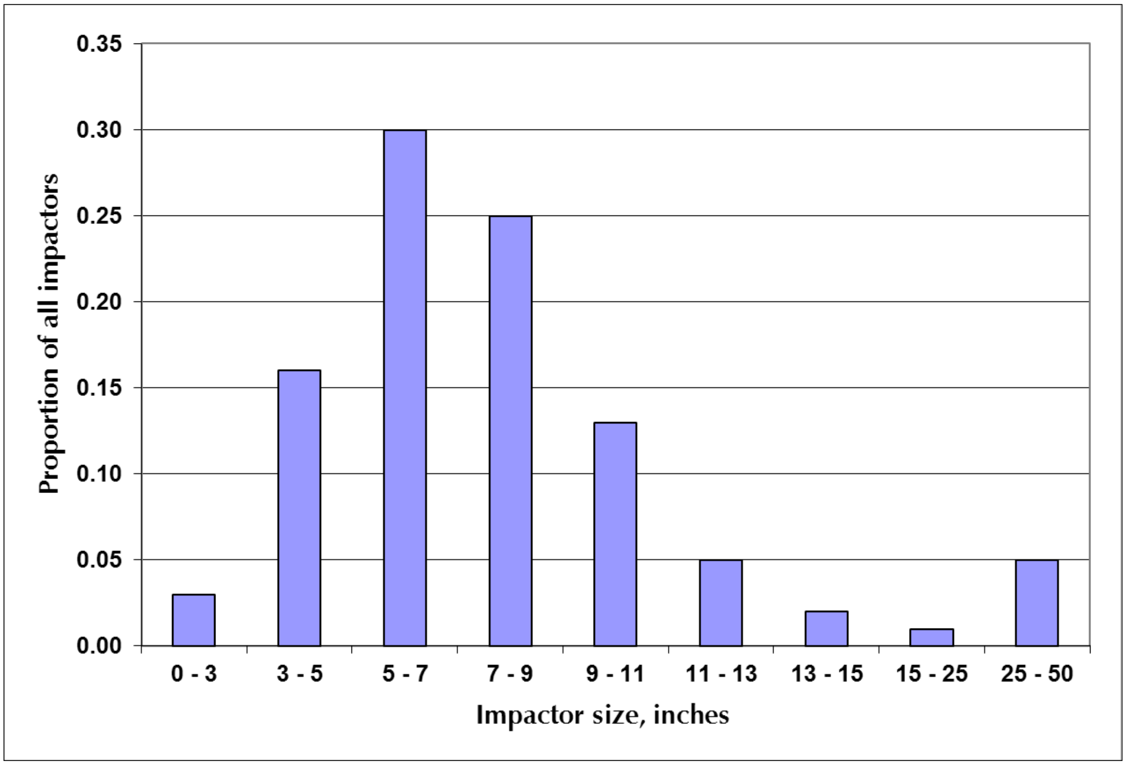

Figure 7. Assumed impactor distribution

9. Likelihood of Puncture

Table 1 (below) presents the results of this analysis for two different car designs over the three different derailment initiation speeds considered. For the base car (7/16" outer shell), at 40 mph, the expected number of punctures is 5. Distribution of the number of punctures covering 70% of the scenarios across the 18 simulations ranges from 3 to 7 punctures. It is estimated that 20% of the punctures could happen on the same car. In other words, since the expected number of punctures for 7/16" shell at 40 mph is 5, the expected number of cars punctured for this scenario is 4.

As observed, the model is predicting that an alternate tank design with a 9/16" shell will perform 16% better, in a 40 mph derailment, than a car with a 7/16" shell. The model also predicts that for the same alternate car, the risk of puncture will be 50% less if the derailment happened at 30 mph rather than 40 mph.

For the derailment simulations conducted at 40 mph, the expected (average) number of derailed cars is 21 (this applies to both tank designs). Across the 18 simulations conducted at 40 mph, the distribution of the number of cars derailed covering 70% (2-sigma) of the scenarios ranges from 16 to 25 cars.

In a separate FRA analysis of the effects of plumes emanating from punctured LNG tank cars in a derailment, it was assumed, as the worst case, that five adjacent tank cars were punctured and leaking. From the current work, it was observed that about 70% of the punctures happen in the first 8 cars. Therefore, this work shows that the worst-case assumption in the plume analysis is reasonable.

Table 1. Summary of Model Results

	Base Car			Alternate Design		
	7/16" Shell, 1/2" Head 1/4" Inner Tank			9/16" Shell, 5/8" Head 1/4" Inner Tank		
Initial Train Speed	**30 mph**	**40 mph**	**50 mph**	**30 mph**	**40 mph**	**50 mph**
Number of Cars Derailed	15	21	28	15	21	28
Most Likely Number of Punctures	2.7	5	7.3	2.1	4.2	6
% Improvement Compared to 7/16" shell	~	~	~	22%	16%	18%
% Improvement Due to Speed Reduction	**40 to 30 mph**	**50 to 40 mph**	~	**40 to 30 mph**	**50 to 40 mph**	~
	46%	32%	~	50%	30%	~

10. Summary

The FRA had previously developed a methodology to estimate the risk reduction resulting from changes in tank car design or operating conditions under derailment conditions, focusing on the likelihood of puncture. This methodology was utilized to evaluate the likelihood of puncture of two different tank car designs intended for the transportation of LNG.

Trains composed of 100 loaded LNG tank cars were simulated to derail from initial speeds of 30, 40, and 50 mph. In order to derive a 'nominal' force spectrum, that reasonably represent typical variations in conditions and circumstances, a set of 18 different simulations were performed at each speed. Parameters representing ground friction, track stiffness, and derailment initiating force were varied to obtain the 18 different scenarios. Two different tank designs were evaluated using the collision impact force results from the derailment simulations:

- Base car: 7/16" thick steel shell with 1/2" thick heads and 1/4" stainless steel inner tank
- Alternate design: 9/16" thick steel shell with 5/8" thick heads and 1/4" stainless steel inner tank

For the base car at a 40 mph derailment speed, the expected number of punctures is 5. It is estimated that 20% of the punctures could happen on the same car. In other words, the expected number of cars punctured for this scenario is 4. The model also predicted that the alternate tank design, with a 9/16" shell, would perform 16% better, in a 40 mph derailment, than the car with a 7/16" shell. The model also predicts that for the same alternate car, the risk of puncture will be 50% less if the derailment happened at 30 mph rather than 40 mph.

11. REFERENCES

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