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Evaluation of Tank Car Sloshing Effects on Rail Safety

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16. Abstract

National Research Council Canada (NRC) was commissioned by Transport Canada (TC) to gather any evidence that movement of liquid in a rail tank car could contribute to derailments of trains carrying liquid dangerous goods. A literature review was performed to assess the state-of-the-art in sloshing research in a variety of applications including rail transport, road vehicles, aerospace and marine transport. Representatives from government and industry in Canada and the United States were consulted to determine the extent to which liquid dangerous goods are shipped in partially filled cars, and if this has ever been a factor in incidents or accidents.

To study the effect of tank car sloshing on derailment risk, a multibody dynamics (MBD) liquid sloshing model was developed and then integrated into an empty tank car MBD simulation model developed and validated with field tests in 2009-12. Hundreds of thousands of dynamic simulations were conducted for the tank car with liquid cargo at various fill ratios and with the equivalent solid cargo on the field test track. The results show that under some conditions tank car sloshing increases the risk of derailment. The detrimental effect on rail safety increases with the increase of outage, trailing tonnage, grade, car length difference, track curvature and speed. It is recommended the liquid sloshing model be improved, and a tool developed for use by regulators and railroads to develop improved guidelines on train marshalling practices.

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sloshing, tank car, rail safety, liquid dangerous goods, multibody dynamics, simulations

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16. Résumé

Le Conseil national de recherches du Canada (CNRC) a été mandaté par Transports Canada (TC) pour recueillir des preuves que le mouvement de liquide dans un wagon-citerne pourrait contribuer au déraillement de trains transportant des marchandises dangereuses liquides. Un examen de la documentation a été réalisé afin d'évaluer l'état de la technologie dans les recherches sur le ballottement dans une variété d'applications, y compris le transport ferroviaire, les véhicules routiers, l'aérospatiale et le transport maritime. Des représentants du gouvernement et de l'industrie au Canada et aux États-Unis ont été consultés afin de déterminer dans quelle mesure les marchandises dangereuses liquides sont expédiées dans des wagons partiellement remplis et si cela a déjà été un facteur dans des incidents ou des accidents.

Pour étudier l'effet du ballottement des wagons-citernes sur le risque de déraillement, un modèle de ballottement de liquide dynamique multicorps (MBD) a été développé et ensuite intégré dans un modèle de simulation MBD de wagons-citernes vides, développé et validé par des essais sur le terrain en 2009-2012. Des centaines de milliers de simulations dynamiques ont été effectuées pour le wagon-citerne avec une cargaison liquide à divers taux de remplissage et une cargaison solide équivalente sur la piste d'essai sur le terrain. Les résultats montrent que, dans certaines conditions, le ballottement des wagons-citernes augmente le risque de déraillement. L'effet préjudiciable sur la sécurité ferroviaire augmente avec l'augmentation du nombre d'arrêts, du tonnage remorqué, de la pente, de la différence de longueur des wagons, de la courbure de la voie et de la vitesse. Il est recommandé d'améliorer le modèle de ballottement des liquides et d'élaborer un outil à l'intention des organismes de réglementation et des chemins de fer afin d'élaborer des lignes directrices améliorées sur les pratiques de formation des trains.

17. Mots clés

ballottement, wagon-citerne, sécurité ferroviaire, marchandises dangereuses liquides, dynamique multicorps, simulations.

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ABSTRACT

National Research Council Canada (NRC) was commissioned by Transport Canada (TC) to gather any evidence that movement of liquid in a rail tank car could contribute or is contributing in any way to derailments of trains carrying liquid dangerous goods.

A literature review was performed to determine the state-of-the-art in sloshing research and identify gaps in existing research related to tank car sloshing. Over 70 references were examined. A variety of applications were covered by the review including rail transport, road vehicles, aerospace and marine transport.

Representatives from companies that load or ship liquid dangerous goods were consulted to determine if liquid dangerous goods are shipped in partially filled cars, and, if they are, what the typical frequency of partial-fill shipments is and what the typical fill level is. Canadian accident and incident data from the Transportation Safety Board of Canada (TSB) were reviewed to determine if sloshing has ever been mentioned or suspected as a contributing factor in an incident. Individuals from TC, TSB, United States Federal Railroad Administration, Association of American Railroads, and the rail industry were consulted to determine if unreported evidence of sloshing had occurred in the past.

Analytical work was conducted to study the effect of tank car sloshing on derailment risk. A multibody dynamics (MBD) liquid sloshing model was developed for a railway tank car with formulas generated based on available Finite Element Analysis data. The new liquid sloshing model was integrated into an empty tank car MBD simulation model developed in 2009-12 to study the impact of curvature on track geometry safety standards. The ability of the empty tank car model to predict wheel forces accurately in curves was validated previously on more than 523 miles of track with 1,340 curves. The integration of the liquid sloshing model and empty tank car model provided an MBD model capable of accurately predicting the dynamic behaviour of a tank car with a wide range of liquid payloads as it travelled over the field-test track. For comparison purposes, a solid-payload tank car model was developed by taking the validated empty tank car model and adding a non-moving payload located in the bottom of the tank.

Hundreds of thousands of dynamic simulations were conducted for the tank car with liquid cargo at various fill ratios and with the equivalent solid cargo on more than 1,000 measured curves. The results show that under some conditions tank car sloshing could increase the risk of derailment. The detrimental effect of tank car sloshing on rail safety increases with the increase of outage, trailing tonnage, grade, car length difference, track curvature and train speed. It is recommended that further investigation be performed to improve the liquid-slosh model and develop a tool that can be used by regulators and railroads to develop improved guidelines on train marshalling practices

ACRONYMS

AAR	Association of American Railroads
ABAQUS	A simulation package for modeling stresses using FEA
ADAMS	A MBD simulation package
ALE	Arbitrary Lagrangian Eulerian is an approach to FEA modeling that enables the advantages of the Eulerian and Lagrangian approaches
ANSYS	A simulation package for modeling stresses using FEA
ANSYS Fluent	A CFD simulation package
API	American Petroleum Institute
Buff in-train force	See definition for In-train force
Cant deficiency	Positive cant deficiency exists when a train is travelling through a curve faster than the balance speed, and thus produces a net lateral force to the outside of the curve. It is measured in inches in North America and is the amount of additional superelevation (lifting of the outside rail above the inside one) that would need to be added to achieve balance at the given speed.
CFD	Computational fluid dynamics
CG	Centre of gravity of a mass
CN	Canadian National Railway
Coupler	An appliance for connecting railcars and/or locomotives together, sometimes referred to as a “drawbar”
Coupler angle	The angle between the centrelines of two connected couplers
CP	Canadian Pacific Railway
Distributed power	A specific type of locomotive control system that allows powered locomotives to be located at one or more remote locations along the length of a train.
Draft in-train force	See definition for In-train force
EMM	Equivalent mechanical model
FDM	Finite difference method, a CFD technique
FEA	Finite element analysis
Fill ratio	A measure of tank fullness that is the height of the liquid surface from the tank bottom divided by the tank diameter
FRA	United States Federal Railroad Administration
FVM	Finite volume method, a CFD technique
GRL	Gross rail loading – the overall weight of one freight car or locomotive, and measured in US tons (1 US ton = 2,000 lb)
In-train force	The steady-steady state and/or abrupt dynamic forces exerted on adjoining railcar couplers and the dynamic interaction that occurs between vehicles in motion due to train weight distribution, train length distribution, train speed control, and changes in terrain. These in-train forces are either buff (compression) or draft (tension). When the train is on straight track, the in-train force is principally a longitudinal force. When the train negotiates a curve, the in-train force is roughly in the tangential direction of the curve; thus, the in-train force applied to the coupler at each end of a car in a curve has two components – a longitudinal in-train force that is parallel to the car centreline, and a lateral in-train force that is perpendicular to the car centreline. Only steady-state in-train force is considered in this study.

IWS	Instrumented wheelset; a device for measuring dynamic forces at the wheel-track interface
kip	An imperial unit of force equal to 1,000 lb
Lateral in-train force	See the definition for In-train force
Longitudinal in-train force	See the definition for In-train force
LS-DYNA	A simulation package for modeling stresses using FEA and fluid motions using CFD
L/V	Single-wheel L/V, a key ratio in railway design, relating the lateral force L exerted by a train's wheel on the rail to the downward force V exerted by the wheel at the same time
MBD	Multibody dynamics, a method of modeling the dynamic behaviour of mechanical systems in response to input excitation
NRC	National Research Council Canada
NUCARS	A MBD simulation package for modeling rail car - track interaction
Outage	A measure of tank fullness that is either in length (the height from the top of the tank to the liquid surface) or percentage (the unfilled volume over the full volume)
Pendulum length ratio	The ratio of pendulum length (in a pendulum model) over tank radius
Pendulum mass ratio	The ratio of pendulum mass of liquid (in a pendulum model) over the total mass of liquid
Pendulum model	A MBD model of the sloshing of a liquid payload using a mass on a pendulum
RODS	TSB Rail Occurrence Database System
SIMPACK	A MBD simulation package
Solid model	A MBD model of the liquid payload that remains stationary in the bottom of the tank
SPH	Smoothed particle hydrodynamics
Spring mass model	A MBD model of the sloshing of a liquid payload using a mass suspended with springs
Superelevation	The difference in height between the outer rail and the inner rail in a curve
TC	Transport Canada
Trailing tonnage	The total weight measured in US tons (1 US ton = 2,000 lb) of all railcars following behind the railcar in question back to the end of the train, or back to the next operating locomotive in the case of a train with a distributed power configuration
TSB	Transportation Safety Board of Canada
UM	Universal Mechanism is a MBD software package
VAMPIRE	A MBD simulation package for modeling rail car - track interaction
Wheel unloading ratio	$\Delta Q/Q$, a key ratio in railway design, relating Q, the nominal vertical force the wheel places on the rail, with ΔQ, the wheel unloading force

EXECUTIVE SUMMARY

Introduction

Derailments involving crude oil trains have raised concerns among some regulators and stakeholders that sloshing, or bulk movement, of crude oil in tank cars is potentially increasing the risk of derailment of trains carrying this commodity. Sloshing has been assumed to be the cause of a number of normal-train-operation incidents in which large surge pressures exerted on pressure relief valves led to their activation and the accidental release of lading. This issue was resolved in the early 2000s by increasing the activation pressure of pressure relief valves and including surge protection in their design. However, the solution did not address the underlying possibility that a less-than-full liquid level causes sloshing of the product within the tank. Because of this, it is theorized that sloshing may increase the derailment risk of trains carrying liquids by changing the center of gravity in cars moving around corners or by irregular forces due to the movement of the liquid inside the tank.

National Research Council Canada (NRC) was commissioned by Transport Canada (TC) to gather evidence (if any) that movement of liquid in a tank car (i.e., sloshing) could contribute or is contributing in any way to derailments of trains carrying liquid dangerous goods, and if the evidence supports further investigation. This might include, but not be limited to, physical testing, Finite Element Analysis and detailed evaluations of the effects of fill ratio and commodity type on rail safety.

The following three investigations were conducted:

Literature Review

A literature review was performed to determine the state-of-the-art in sloshing research and identify gaps in existing research related to tank car sloshing. Over 70 references were examined in a variety of applications including rail transport, road vehicles, aerospace, and marine transport. The primary focus was on physical tests and computer simulations related to rail transport.

The review found that a wide range of physical tests of sloshing on mainly rectangular and cylindrical tanks have been conducted, but they are expensive to perform.

The review also found that a range of mathematical computer simulation models have been developed to model sloshing in partially filled containers. The most accurate are those using Computational Fluid Dynamics (CFD). The dynamic behaviour of railcars and other vehicles is normally studied using multibody dynamics (MBD) models. While it is possible to combine MBD and CFD models together to get a direct model with the capabilities of both, it is typically too computationally expensive to use on its own to investigate tank car sloshing.

Instead, a range of equivalent mechanical models (EMMs) are used to represent sloshing in MBD models. The standard approach is to use a pendulum or spring-mass system that models the sloshing motions of the liquid. An ideal EMM is one in which a number of specific conditions are met (e.g., mass and moments of inertia of the EMM and sloshing fluid in the physical system should be similar) to ensure the EMM is a good representation of the sloshing fluid for the purpose of conducting an MBD simulation. EMM parameters (e.g., masses, pendulum lengths, spring stiffnesses) are calibrated using CFD simulations of sloshing. Different sloshing motions (e.g., lateral sloshing and longitudinal sloshing) require different EMM models.

The review describes 14 publications on sloshing in rail transport describing work between 1954 and 2017. EMMs were first described in work published in 1998, and continue to be part of the work published in 2017. In the latest EMM publication, an improved pendulum model was used, and simulations were performed on tangent track and a curve with a 650 m radius at speeds in the range of 40 – 120 km/h. Four different partial fill levels were considered between 66% and 98%. On the curved track at speeds of 40, 60 and 120 km/h a significant increase in the potential for derailment was found. The most significant potential for derailment occurred with a partial fill of 66%.

Taken as a whole, the literature review suggested several ways in which rail operations may be negatively affected by tank car sloshing:

- potential for more derailments;
- increased magnitudes and oscillations of longitudinal forces during braking;
- increased overturning risks;
- increased hunting instability at high speed.

No reports were found of stochastic studies to investigate the safety performance of railway tank cars operating in a wide range of load and operating conditions.

Review of TSB Accident and Incident Data and a Survey of Industry Experts

Canadian accident and incident data from the Transportation Safety Board of Canada (TSB) was reviewed to determine if sloshing has ever been mentioned or suspected as a contributing factor in an incident. Industry experts from companies that load or ship liquid dangerous goods, or manufacture tank cars for this purpose, were interviewed to determine if liquid dangerous goods are shipped in partially filled cars, and, if they are, what a typical frequency of a partial-fill shipment is, and what the fill levels of any partially filled cars are. Experts from Transport Canada, TSB, United States Federal Railroad Administration (FRA), and the Association of American Railroads (AAR) were also interviewed to determine if unreported evidence of sloshing had occurred in the past.

The TSB was not aware of any TSB investigations where liquid sloshing was determined to be the cause of a derailment. A search of TSB's published accident reports showed that none of the accidents had sloshing identified as a cause.

A search of the TSB Rail Occurrence Database System (RODS) database identified a report where sloshing was described in relation to a yard derailment, but it is not known if sloshing played a role in this yard derailment or it was simply observed to occur due to the derailment or other car movements.

In one RODS item (RODS R06V0272), a worker was injured when a "***sloshing*** *action from the tank moved the car forward".* This is the only instance of sloshing being attributed as a factor in a safety related incident. The incident took place in a yard, not on mainline track, and did not involve a derailment. The potential for sloshing to cause a car to move unexpectedly in yard or switching operations was later confirmed by discussions with experienced industry experts. None of the experts interviewed knew of an instance where an underfilled tank car had caused a safety issue or a concern, and in general sloshing of liquids within a tank car during transit on mainline track was not seen as a safety concern.

In the interviews and other forms of communication that took place with rail industry experts, none of the experts knew of a case where sloshing had been found to be the cause of a derailment or mainline accident. There was broad agreement on the potential for liquids to slosh around in a tank car, and for the amount of sloshing to be dependent on the fill level. Most stated that a high percentage of tank cars are filled at the level of 90% to 95% due to economics of the shipping industry.

Several experts independently stated that the possibility for partially loaded tank cars to operate in service does exist, and occurs in practice under the following three circumstances:

- A buyer orders less than a tank load of a specialty commodity, so a fully loaded tank may then be partially unloaded, or a partially loaded tank is made and shipped. This type of load condition would be a single tank, not a unit-train situation.
- A tank designed for a nominal density commodity is used to ship a similar commodity that is slightly denser. The result is that the weight limit of the tank is reached before the volume limit is. This potential is common with some commodities, where the density can vary depending on the commodity (and temperature). This type of partially loaded tank could occur as a single car or as a unit train.
- A track segment with weight restrictions will place a limit on the weight of cars passing, such that larger volume tanks must be partially loaded to meet this weight restriction. For example, if a tank car designed to have gross rail load of 286,000 lb when filled to a 98% fill ratio is to be routed over a section of track with a 263,000 lb limit, this car would need to be filled with less than 98% volume to reach the load limit. This type of partial load may be more common than the first two listed above, and may occur as single cars or as unit trains.

Two experts reported that the general understanding in the industry is that, in cases where a tank car is filled to a lower volume, the overall centre of gravity of the tank becomes lower, and this, combined with the lower weight, would make the partially filled car less susceptible to tipping (under static conditions).

In summary, the industry experts advised that:

- sloshing of liquids within a rail tank car has never been attributed as the cause of a derailment or a mainline accident. (This does not mean that sloshing has not ever been the cause of a derailment, only that it has not to date been attributed as being the cause of a derailment.);
- sloshing does occur during yard and switching operations, where the sloshing forces may cause a car to move unexpectedly. There is one reported injury related to this type of sloshing action during a yard operation;
- sloshing forces do cause train action motions that locomotive engineers have noted;
- tank cars can be partially filled as part of regular shipping operations, and may occur as single cars or as several cars in a unit train consist.

Dynamic Simulations

Analytical work was conducted to assess the extent to which movement of liquid in a tank car could contribute to derailments of trains carrying liquid dangerous goods.

The work made use of an empty tank car simulation model that was developed in a 2009-2012 project performed by NRC, TC, Federal Railroad Administration (FRA), Canadian Pacific Railway (CP), and Canadian National Railway (CN) to study the impact of curvature on track geometry safety standards. Field tests were conducted on more than 523 miles of track with

1,340 curves on four subdivisions of CN and CP main track between Vancouver and Kamloops, BC. The car was equipped with two instrumented wheelsets (IWSs) to measure vertical, lateral and longitudinal wheel-rail interaction forces, along with accelerometers, gyroscopic pitch and roll transducers and displacement transducers. NRC developed a MBD model of the empty tank car using VAMPIRE, a MBD software product that lets users simulate the dynamics of rail vehicles as they operate over track with user-defined geometry. The 2012 project report contains comparisons between the measured and simulated time histories of wheel forces that show the vehicle and track model developed can simulate car performance in curves with a high degree of fidelity.

A pendulum model was developed in 2017 to simulate the effect of sloshing in railway tank cars with formulas generated based on Finite Element Analysis data. The sloshing model was then incorporated into the validated MBD empty tank car model from the 2012 project.

For comparison purposes, a solid-payload tank car simulation model was developed by taking the validated empty tank car model and adding a non-moving payload located in the bottom of the tank.

The validated empty tank car model, the solid-payload model and the liquid sloshing simulation model were all used to study the effects of tank car sloshing on rail transportation safety. Hundreds of thousands of dynamic simulations were conducted for the tank car with liquid cargo at various fill ratios, and with equivalent solid (i.e., rigid) cargo, on more than 1,000 measured curves. The liquid was assumed to have a density of 1,000 kg/m^3, the upper limit of the range of densities given by API for heavy crude oil (920 -1,000 kg/m^3).

The conditions under which tank car sloshing could have a detrimental effect on rail transportation safety were identified and evaluated. The simulation results show that tank car sloshing has a much higher impact on wheel unloading than on wheel climbing. Therefore, the wheel unloading ratio was used in this study as a safety measure to analyze the impact of tank car sloshing on rail transportation safety.

The simulations show, as expected, that sloshing does not cause any significant wheel unloading (and hence safety issues) at high fill ratios (e.g., 95%). However, as the fill ratio is lowered towards 50%, sloshing can become an issue in some circumstances.

The simulations also show that, for a given tank car fill level, there are two principal factors – high levels of cant deficiency and high levels of lateral in-train force – that can lead to dangerous levels of slosh-related wheel unloading, and hence have a significant detrimental effect on tank car safety.

The simulation results show that, on the measured curves, when there is no in-train force, the maximum effect of tank car sloshing on wheel unloading is about 5% at cant deficiencies up to 3 inches and 8% at cant deficiencies up to 4 inches. The effect of tank car sloshing on wheel unloading increases with cant deficiency. At cant deficiencies of less than 1 inch, the effect of tank car sloshing is small.

The analysis and graphs presented in this report are limited to cases where the cant deficiency was lower than or equal to 3 inches, the cant deficiency limit in Canada. Some of the 1,340 curves that were measured in field tests described in 2012, and were available for use in this study, had cant deficiencies that were over 3 inches. These cases were studied, but the results are not included in this report.

Lateral in-train force is equal to coupler force (i.e., the longitudinal in-train force) multiplied by the sine of coupler angle. In general, steep grades and high trailing tonnage lead to high coupler forces, and large differences between the length of the tank car in question and a shorter adjoining car lead to higher coupler angles.

The largest difference in wheel unloading ratio[1] predicted by the liquid model relative to that predicted by the solid model was about 35%, and it occurred in the case where there was a 70% fill ratio, 2 to 3 inches of cant deficiency, and a 17 kip lateral in-train force. Thus, if a solid model were used to estimate the wheel unloading instead of a liquid sloshing model, for some combinations of curve, speed and grade, the wheel unloading would be underestimated by 35 percentage points (i.e., the wheel unloading ratio would be estimated to be 45% instead of 80%). Thus, it is critical that future investigations of tank car safety behaviour in this operating regime make use of effective dynamic sloshing models.

The effect of tank car sloshing on derailment risk increases with the increase of lateral in-train force or the decrease of fill ratio. Therefore, special attention should be paid to tank cars with a low fill ratio and high lateral in-train force. For example, a lateral in-train force of 15 kip could occur if the tank car was connected to a much shorter car and then placed at the front of the train. In this circumstance, tank car sloshing could increase wheel unloading by 35% at a fill ratio of 50%.

It is recommended that a tank car with a low fill ratio be connected to cars with the same or longer car length. If a tank car with a low fill ratio has to be connected to a much shorter car, it is recommended that the car be placed as far behind a locomotive as possible. As shown in the flowchart in Figure 4-31, there are many conditions that can increase the effect of tank car sloshing on derailment risk. They should all be considered to accurately evaluate the derailment risk of a partially filled tank car.

It is recommended that further investigation be conducted to develop a tool that can be used for regulators and the railroads to improve guideline on train marshalling practices.

Summary and Recommendations

Literature Review

A tank sloshing literature review of over 70 references was performed. The literature suggests that several rail operating conditions may be negatively affected by sloshing:

- potential for more derailments;
- increased magnitudes and oscillations of longitudinal forces during braking;
- increased overturning risks;
- increased hunting instability at high speeds.

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[1] Wheel unloading ratio, ΔQ/Q, is a key ratio in railway design that relates Q, the nominal vertical force the wheel places on the rail, with ΔQ, the wheel unloading force (i.e., the change in vertical force). High wheel unloading ratios are associated with an increased likelihood of the railcar rolling over.

It is recommended that further research be conducted that includes both physical testing and computer simulations to better understand these tank car sloshing risks.

Review of TSB Accident and Incident Data and a Survey of Industry Experts

The TSB was not aware of any recent TSB investigations where liquid sloshing was determined to be the cause of a derailment. The TSB RODS database identified a report where sloshing was described in relation to a yard derailment but it is not known if sloshing played a role in this yard derailment or it was simply observed to occur due to the derailment or other car movements.

In one RODS item (RODS R06V0272) a worker was injured when a "***sloshing*** *action from the tank moved the car forward".* This is the only instance of sloshing being attributed to a safety related incident. This took place in a yard, not on mainline track, and did not involve a derailment. The potential for sloshing to cause a car to move unexpectedly in yard or switching operations was later confirmed by discussions with experienced industry experts. None of the experts interviewed knew of an instance where an underfilled tank car had caused a safety issue or a concern, and in general sloshing of liquids within a tank car during transit on mainline track was not seen as a safety concern.

To summarize:

- Sloshing of liquids within a rail tank car has never been attributed as the cause of a derailment or a mainline accident. (This does not mean that sloshing has not ever been the cause of a derailment, only that it has not to date been attributed as being the cause of a derailment.)
- Sloshing does occur during yard and switching operations, where the sloshing forces may cause a car to move unexpectedly. There is one reported injury related to this type of sloshing action during a yard operation.
- Sloshing forces do cause train action motions that locomotive engineers have noted.
- Tank cars can be partially filled as part of regular shipping operations and may occur as single cars or as several cars in a unit train consist.

Dynamic Simulations

Analytical work was conducted to assess the extent to which movement of liquid in a tank car could contribute to derailments of trains carrying liquid dangerous goods.

A new pendulum equivalent mass model (EMM) was developed to simulate the effect of liquid sloshing in railway tank cars with formulas generated based on Finite Element Analysis data. This liquid sloshing model was then incorporated into the empty tank car MBD model that NRC developed and validated in a 2009-2012 study on the impact of curvature on track geometry safety standards. The ability of the empty tank car model to predict wheel forces accurately in curves was validated using wheel force data obtained from Instrumented Wheelset (IWS) transducers installed on an empty tank car and operated over more than 523 miles of CN and CP track with 1,340 curves between Vancouver and Kamloops, BC. While the majority of the curves were between 2° and 8°, 18 very sharp curves of more than 10° were included. The sharpest curvature was about 11.4°.

The new pendulum model of liquid slosh, the empty tank car model from 2009-12, and the track geometry data from the 2009-12 were combined together to allow the simulation of a tank car with a sloshing payloads of various sizes, as it operates over more than 1,000 of the curves from the 2009-12 study.

For comparison purposes, a solid-payload tank car model was also developed by taking the validated empty tank car model and adding a non-moving payload located in the bottom of the tank.

Hundreds of thousands of dynamic simulations were conducted for the tank car with liquid cargo at various fill ratios and with equivalent solid (i.e., rigid) cargo on more than 1,000 measured curves. The liquid was assumed to have a density of 1,000 kg/m^3, the upper limit of the range of densities given by API for heavy crude oil (920 -1,000 kg/m^3).

The simulation results show that tank car sloshing has a much higher impact on wheel unloading than on wheel climbing. Therefore, the wheel unloading ratio used in this study as a safety measure to analyze the impact of tank car sloshing on rail transportation safety.

The largest difference in wheel unloading ratio predicted by the liquid model relative to that predicted by the solid model was about 35%, and it occurred in the case where there was a 70% fill ratio, 2 to 3 inches of cant deficiency, and a 17 kip lateral in-train force. Thus, if a solid model were used to estimate the wheel unloading instead of a liquid sloshing model, for some combinations of curve, speed and grade the wheel unloading would be underestimated by 35 percentage points (i.e., the wheel unloading ratio would be estimated to be 45% instead of 80%). ***It is strongly recommended that future investigations of tank car safety behaviour in this operating regime make use of effective dynamic sloshing models.***

The simulation results show that, on the measured curves, when there is no in-train force, the maximum effect of tank car sloshing on wheel unloading is about 5% at cant deficiencies up to 3 inches and 8% at cant deficiencies up to 4 inches. The effect of tank car sloshing on wheel unloading increases with cant deficiency. At cant deficiencies less than 1 inch, the effect of tank car sloshing is small.

The EMM model of tank car sloshing used for this study was based on a Finite Element Analysis simulation model of liquid sloshing in a tank, without having any physical measurements of actual fluid motions. ***It is recommended that physical tests of tank car sloshing be conducted to validate and improve the simulation models.***

The effect of tank car sloshing on derailment risk increases with the increase of lateral in-train force or the decrease of fill ratio. ***Therefore, it is recommended that special attention be paid to tank cars with low fill levels and high lateral in-train forces.*** For example, a lateral in-train force of 15 kip could occur if the tank car was connected to a much shorter car and then placed at the front of the train. In this circumstance, tank car sloshing could increase wheel unloading by 35% at a fill ratio of 50%.

Lateral in-train force is equal to coupler force multiplied by the sine of coupler angle. In general, high grade and high trailing tonnage lead to high coupler force, and high car length difference between the car in question and a shorter adjoining car leads to higher coupler angle.

It is recommended that a tank car with low fill ratio be connected to cars with the same or longer car length. If a tank car with low fill ratio has to be connected to a much shorter car, it is recommended that the car be placed as far behind a locomotive as possible. As shown in the flowchart in Figure 4-31, there are many conditions that can increase the effect of tank car sloshing on derailment risk. They should all be considered to accurately evaluate the derailment risk of a partially filled tank car.

The simulation results show that the effect of tank car sloshing on wheel unloading, and hence on tank car safety, is increased when there are significant reductions in fill level, high levels of cant deficiency, and high levels of lateral in-train force. However, this report does not take into account the probability of these individual events occurring, or the likelihood that a given combination would occur simultaneously. **It is recommended that further investigations be conducted to identify or estimate probability distributions for reductions in fill ratio, high levels of cant deficiency and high levels of lateral in-train force, and use them to estimate the probability of tank car sloshing leading to wheel unloading that could potentially cause a derailment.**

The simulation results in this report do not take into account the consequences (e.g., the cost) of an accident where tank car sloshing was a significant factor. **It is recommended that the consequences (e.g., costs) of the derailment be taken into account in future investigations into the risk of tank car sloshing and the possibility that it could cause a derailment.**

It is recommended that further investigation be conducted to improve liquid-slosh model and develop a tool that regulators and railroads can use to develop improved guidelines on train marshalling practices. This would include, for example, various states of wear for wheels, friction wedges and other car components and systems.

An international workshop on the effects of tank car sloshing on rail transportation safety was held in Ottawa on 25 August 2017, with participants from academia, industry, government and R&D centres in Canada, USA, Russia, Australia and China. Findings on the effect of tank car sloshing from NRC and other research organizations have been presented***. A substantial amount of positive feedback from participants was received regarding the establishment of an international collaborative initiative on railway tank car sloshing.***

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1 INTRODUCTION

Derailments involving crude oil trains have raised concerns among some regulators and stakeholders that sloshing, or bulk movement, of crude oil in tank cars is potentially increasing the risk of derailment of trains carrying this commodity. Sloshing has been assumed to be the cause of a number of normal-train-operation incidents in which large surge pressures exerted on pressure relief valves led to their activation and the accidental release of lading. This issue was resolved in the early 2000s by increasing the activation pressure of pressure relief valves and including surge protection in their design. However, this solution did not address the underlying possibility that a less-than-full liquid level increases sloshing of the product within the tank. Because of this, it is theorized that sloshing may increase the derailment risk of trains carrying liquids by changing the center of gravity in cars moving around corners or by irregular forces due to the movement of the liquid inside the tank.

National Research Council Canada (NRC) was commissioned by Transport Canada (TC) to gather evidence (if any) that movement of liquid in a tank car (i.e., sloshing) could contribute or is contributing in any way to derailments of trains carrying liquid dangerous goods, and determine if the evidence supports further investigation. This might include, but not be limited to, physical testing, Finite Element Analysis and detailed evaluations of the effects of fill ratio and commodity type on rail safety.

A literature review was performed in order to determine the state-of-the-art in sloshing research and identify gaps in existing research related to tank car sloshing. Over 70 references were examined in a variety of applications including rail transport, road vehicles, aerospace and marine transport. The primary focus was on physical tests and computer simulations related to rail transport. Several operational conditions that may be negatively affected by sloshing are identified as potential areas for future research.

Companies that load or ship liquid dangerous goods were interviewed to determine if liquid dangerous goods are shipped in partially filled cars, and, if they are, what a typical frequency of a partial-fill shipment is and what the fill levels of any partially filled cars are. Canadian accident and incident data from the Transportation Safety Board of Canada (TSB) was reviewed to determine if sloshing has ever been mentioned or suspected as a contributing factor in an incident. Individuals from TC, TSB, United States Federal Railroad Administration (FRA), Association of American Railroads (AAR), and the rail industry were interviewed to determine if unreported evidence of sloshing had occurred in the past.

Analytical work on the effect of tank car sloshing was conducted based on an empty tank car model validated with test data from Instrumented Wheelset (IWS) measurements and a liquid sloshing model developed based on finite element analysis (FEA) data. Hundreds of thousands of dynamic simulations were conducted for the tank car at various fill ratios and in-train forces on more than 1,000 measured curves. The conditions under which tank car sloshing could have a significant effect on derailment risk were identified and evaluated.

2 LITERATURE REVIEW

2.1 Introduction

In order to respect weight limits as set out in Section 5.5 of the Transportation of Dangerous Goods Regulations, tank cars may be sometimes be operated in the partially loaded condition. The amount of outage in the tank depends on the density of the liquid cargo. When partially loaded, the free surface of the liquid is able to undergo motions as the tank is subjected to various accelerations. The free surface motions of the liquid are caused by sloshing.

A literature review was performed to determine the state-of-the-art in sloshing research. A particular emphasis was placed on rail tank cars. Over 70 documents related to sloshing were reviewed. The documents cover sloshing in rail tank cars ([1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19]), road vehicles ([20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36]), road vehicle fuel tanks ([37], [38]), marine transportation ([39], [40], [41], [42], [43]), aerospace vehicles ([44], [45], [46], [47], [48]) and storage tanks ([49], [50] , [51], [52]). Approximately one-quarter of the documents were related to rail transportation, of which the most relevant are: [10], [11], [12], [13], [14], [15] , [16], [17], [18], [19].

The contents of the documents were varied in their scope: some described mathematical and computer modelling, while others provided results of physical testing. A few of the documents were rail-related news articles and commentary which discussed possible issues sloshing may present to the rail industry, but these generally did not provide any data on the subject. The following sections summarize the key findings from the literature review. Emphasis is placed on the modelling approaches used and the references directly related to rail transport.

2.2 Physical Tests

Physical tests have been used to learn more about sloshing under various conditions and to validate mathematical and computer models. A good summary of experimental sloshing studies can be found in [53]. Physical tests were performed on mainly rectangular and cylindrical tanks filled with various fluids. Numerous excitation types were applied in multiple directions. The key ideas from the body of experimental work were that sloshing depends on the amount of outage in the tank, the dimensions of the tank, the amplitude and frequency of excitation, and the density of the liquid. Physical tests of partially loaded rail tank cars include impact testing ([10], [2], [17]), harmonic roll [10], static lean [10], and braking [10].

2.3 Mathematical and Computer Models

Mathematical and computer analyses provide a safe, repeatable and relatively inexpensive (compared to physical testing) means to study sloshing. In addition, quantities of interest can be approximated at any location in space and time.

When modelling sloshing in a partially filled container, it is important to accurately determine the pressure distribution, the forces, moments, and the natural frequencies of vibrations of the fluid.

Sloshing can be a very complex phenomenon, as several different sloshing motions can occur with respect to a free liquid surface, such as simple planar, nonplanar, rotational, irregular beating, symmetric, asymmetric, quasi-periodic and chaotic [54].

2.3.1 *Analytical Solutions*

Analytical solutions are typically available for only very limited situations that have very little practical value. The difficulty arises due to the nonlinearity presented by the dynamic nature of the free surface. Therefore, analytical solutions are limited, and computer (numerical) solutions must be obtained to study liquid sloshing in moving vehicles.

2.4 Computer Models

Computer models are frequently used to study the effect of sloshing on the safety of partially loaded vehicles. Computer models can give approximate numerical solutions to mathematical problems when analytical solutions are not available. To understand sloshing effects on rail safety there are three important considerations: vehicle motions, fluid motions, and stresses in the vehicle or container structures.

2.4.1 *Vehicle Motions*

The movements of railcars and other similar vehicles are normally studied using multibody dynamics (MBD). The vehicles are modelled as a number of different rigid bodies connected by kinematic constraints such as joints and/or force elements such as springs and dampers. The outputs from this type of analysis are the displacements, velocities, and accelerations of the vehicle and its components. Common commercial MBD software packages include ADAMS, SIMPACK, NUCARS, VAMPIRE, and UNIVERSAL MECHANISM (UM).

2.4.2 *Vehicle Stresses*

The impact of fluid motion on the stresses in the tank or car structure can be studied using Computational Mechanics (CM). The motions of the liquid in the partially filled tanks create loads that are applied to the structure. Finite element analysis (FEA) is the approach most often used to solve this type of problem. ANSYS, LS-DYNA, and ABAQUS are some of the more common commercial FEA software packages used to study vehicle stresses.

2.4.3 *Fluid Motions*

Movement of the fluid is best modelled using the techniques of Computational Fluid Dynamics (CFD). The underlying numerical techniques are commonly the Finite Element Analysis (FEA), Smoothed Particle Hydrodynamics (SPH), the Finite Volume Method (FVM), and the Finite Difference Method (FDM) among others. Commercial CFD software commonly used for sloshing studies includes ANSYS Fluent and LS-DYNA.

The direct use of CFD techniques in MBD vehicle models is typically too computationally expensive to use on its own to investigate tank car sloshing. Therefore equivalent mechanical models (EMM) are typically used to represent sloshing in MBD models. The EMMs are determined using CFD models.

The following two sections provide more details about two of the most frequently used techniques to model fluid motion in a tank – FEA and EMMs.

2.4.3.1 Finite Element Analysis (FEA) Modeling of Slosh

Finite Element Analysis is frequently used to study sloshing in tanks. This choice is partially one of convenience as FEA is widely used to model stresses in the tank. This makes coupling the two models (liquid and tank structure) simpler. FEA uses meshes composed of nodes and elements to obtain an approximate solution. ANSYS, LS-DYNA, and ABAQUS are examples of commercial software commonly used to build FEA models of liquid and tank structures.

There are several types of FEA formulations that can be used to model sloshing in a tank: Lagrangian, Eulerian, and Arbitrary Lagrangian Eulerian. In a Lagrangian approach the mesh deforms with the fluid, while the mesh remains fixed in an Eulerian approach. An Arbitrary Lagrangian Eulerian (ALE) approach enables the advantages of both the Eulerian and Lagrangian approaches to be included in the model. The ALE approach has been successfully used to model sloshing in a tank in many references (e.g. [51], [37], [55] , [38]). LS-DYNA can use several different approaches (ALE, Lagrangian, Eulerian, and SPH) to model sloshing [55] , [56] , [57]. A comparison of the Eulerian, Lagrangian, ALE and SPH approaches was made in [55].

Examples of FEA results for partially filled tank sloshing are shown in Figure 2-1, Figure 2-2, and Figure 2-3. Figure 2-1 shows an FEA mesh (left) and the first mode of vibration (right) for a 2D analysis of sloshing in a tank. The FEA was performed with ANSYS. Figure 2-2 shows an FEA model of a partially filled tank car under side impact, with the impactor in initial contact on the far side of the tank, and the near side of the tank constrained by a vertical wall. A Lagrangian formulation in ABAQUS was used. Figure 2-3 shows the first mode of vibration from FEA performed with ANSYS for a cylindrical tank (left) and a rectangular tank (right).

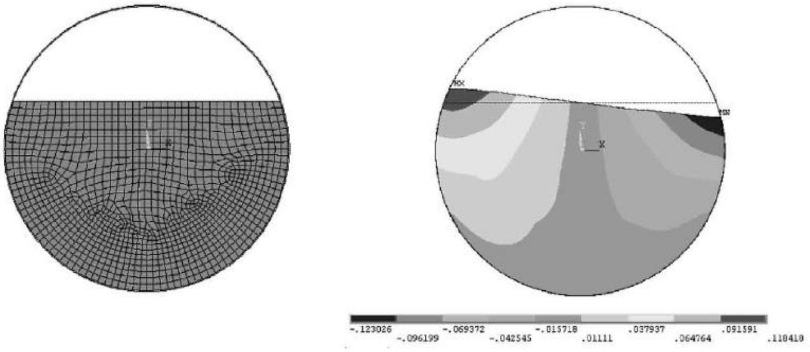


Figure 2-1: Two-dimensional FEA of sloshing: mesh (left), and first mode shape (right) [12].

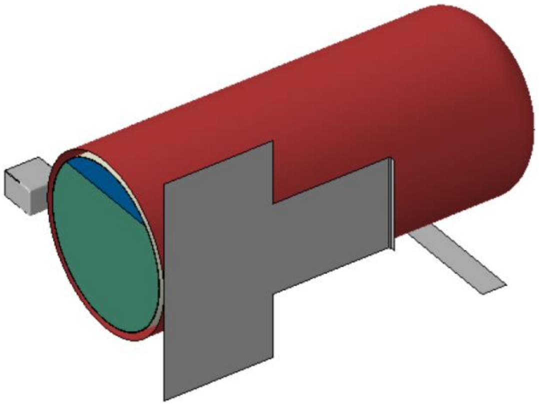


Figure 2-2: A symmetrical three-dimensional model of a partially filled tank car subjected to impactor collision [4].

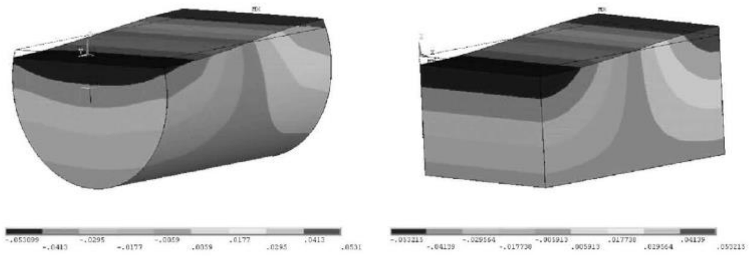


Figure 2-3: The first mode shapes from three-dimensional FEA of sloshing in a circular tank (left) and a rectangular tank (right) [12].

2.4.3.2 Equivalent Mechanical Models (EMMs) of Slosh

Detailed sloshing simulations such as FEA are computationally expensive and difficult to combine with MBD simulations. Therefore, simplified models are often used in place of more detailed CFD simulations. EMMs have been used extensively in rail transport applications (e.g. [11], [12], [13], [14], [15], [16], [17]). Equivalent mechanical models can be used to efficiently model the sloshing behaviour of a moving, partially-filled tank.

The standard approach is to use a pendulum (e.g. [11], [12], [15], [16]) or a spring-mass system (e.g. [12], [13], [14], [17]) in the MBD simulations to account for sloshing. EMMs are simplified models that are calibrated using CFD simulations. EMM simulations generally compare well with results from physical tests, giving reasonable confidence in their suitability to study the effects of sloshing. Examples of spring-mass EMMs are shown in Figure 2-4 and pendulum EMMs are shown in Figure 2-5.

Equivalent mechanical models are derived by satisfying the following [54]:

- the mass and moments of inertia of the EMM and sloshing fluid in the physical system should be similar;
- the centre of gravity location must remain the same as for the physical system when oscillations are small;

- the EMM should have the same modes of vibration and the same damping as the physical system;
- the EMM must apply the same forces and moments to the tank model as the sloshing fluid does in the physical system.

CFD simulations are performed to determine the fundamental frequency of the sloshing and the resulting forces between the liquid and the tank. The oscillation frequency and forces are then used to determine the EMM parameters. When oscillations of the free surface are small (planar motion), systems of simple pendulums or spring-mass systems can be used to model sloshing. As the amplitudes of the oscillations increase (e.g., with non-planar motion and rotational sloshing), compound or spherical pendulums may be used [54].

When a rigid, partially filled container undergoes motion, there are two components to the pressure distribution. A portion of the fluid moves along with the container; the rest is the free-surface motion, which is referred to as convective pressure [54]. EMMs therefore typically have part of the mass moving along with the tank (m_o in Figure 2-4 and Figure 2-5), and the free-surface motion portion is modeled with springs or pendulums.

Figure 2-6 illustrates three distinct sloshing regimes that can occur. Figure 2-6(a) shows the case of small oscillations, which can be modelled with a simple pendulum (or spring-mass system). Figure 2-6(b) describes weakly nonlinear sloshing and can be modelled using a spherical pendulum. Figure 2-6(c) illustrates strongly non-linear motion that is due to quickly changing free surface velocities, which can be modelled using a pendulum that accounts for impacts with the tank wall.

Different sloshing motions require specific EMMs. Parametric sloshing is the motion of the free surface caused by an excitation perpendicular to the initial free surface. Parametric sloshing requires the use of spherical pendulums, as spring-mass models are inadequate to capture resonance. Large accelerations or decelerations (or impact events) can lead to strongly non-linear sloshing behaviour. Longitudinal sloshing can be more severe and generate larger acceleration peaks than lateral sloshing. Sloshing could also create large impacts on the roof of the tank.

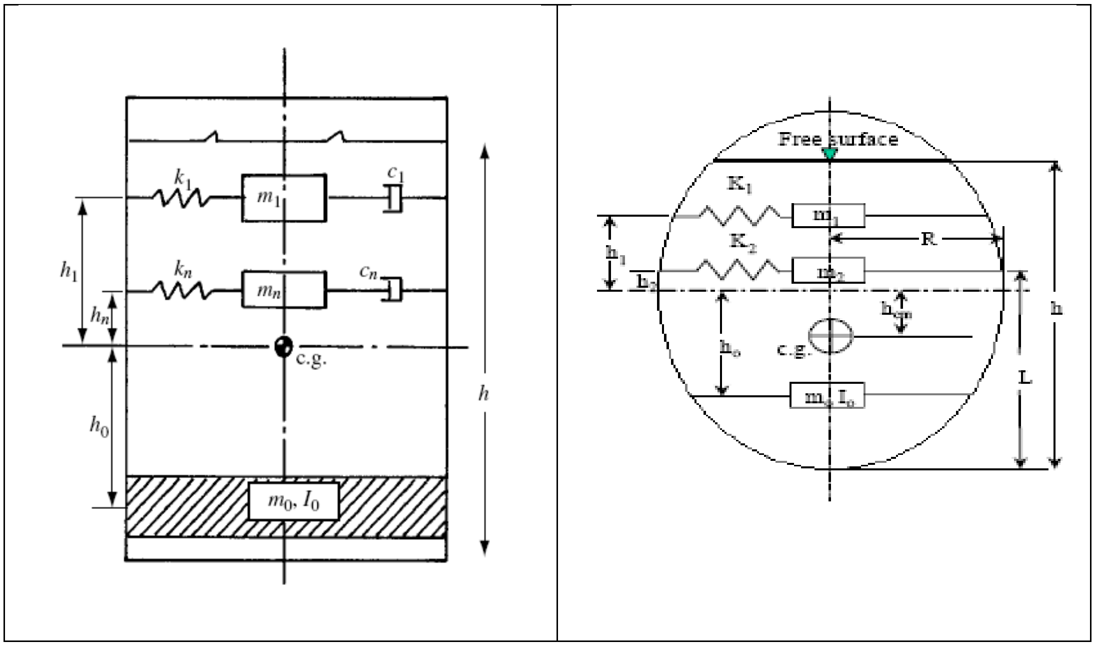


Figure 2-4: Example of an equivalent spring-mass model [54].

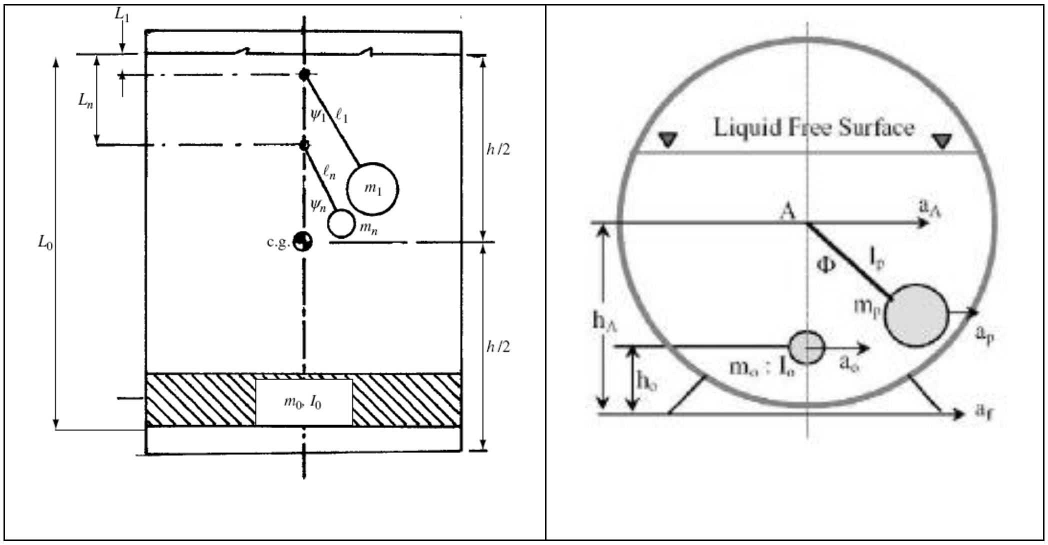
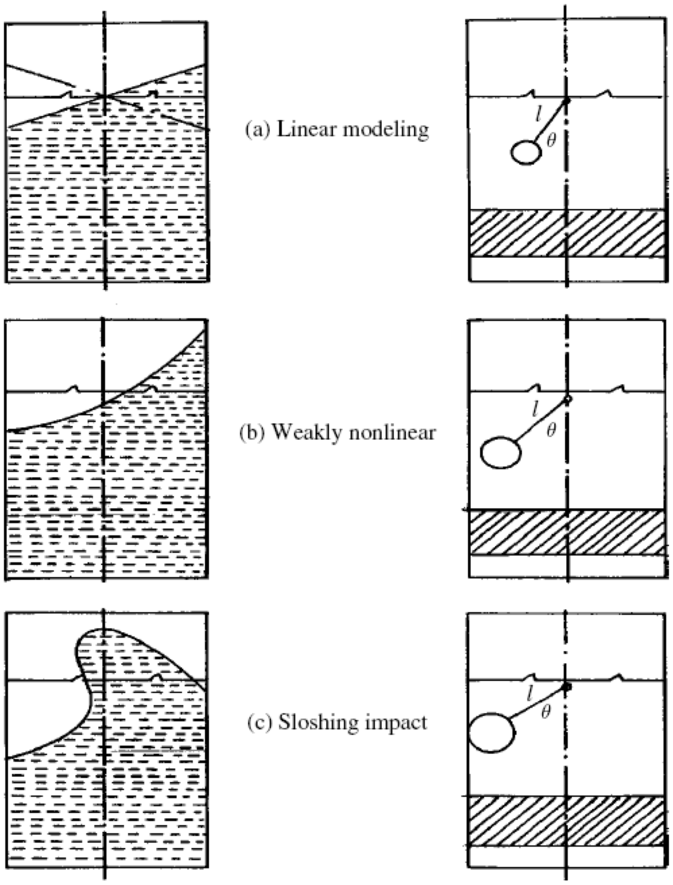


Figure 2-5 Example of an equivalent pendulum model [54], [58].


(a) Linear modeling

(b) Weakly nonlinear

(c) Sloshing impact

Figure 2-6: Three different regimes of sloshing and equivalent mechanical models [54].

2.5 Rail Specific Research

The earliest report of the effect of sloshing related to rail transportation that was found was prepared by US researchers [10] in 1977. The report described a research program conducted between 1954 and 1976. In 1954 physical impact tests were performed at various outages. Stresses in a tank head were measured. Increases in outage resulted in lowered stress levels in the tank head. Compared with the fully loaded case (outage 0%), a 1.4% outage significantly reduced the stress, and a 20% outage reduced the stress to less than 25% of the tank-full condition.

In 1970, physical testing examined the response of a tank car with several outages under harmonic roll (2%, 10% and 50% outage), static lean (2%, 10%, 20%, 30%, 40% and 50% outage) and impact tests (2%, 10%, 20%, 30%, 40% and 50% outage). Increased outages reduced roll amplitudes during harmonic roll tests, gave more stable positions in static lean tests, and reduced the impact forces during impact tests.

In 1974 L/V[2] and lateral stability tests were performed to validate computer models [10]. As part of the test consist the tank car was run at various speeds up to 50 mph with outages up to 39%. Vertical and lateral forces at truck side frame and accelerations were measured. No analysis was done on the tank car. No operational issues were noted.

In 1976, longitudinal sloshing was studied using physical testing of five partially loaded tank cars [10]. Outages ranged from 36-48% and train speeds with braking ranged from 16-80 km/h. An estimated 50,000 lb of extra longitudinal force was created by the sloshing action of the five tank cars. No adverse effects of sloshing were noted and it was estimated that the probability of a dangerous, in-phase resonant response throughout the consist was extremely low.

In 1982, Indian researchers considered two vehicle models with randomly generated track unevenness [59]. The pitching response was found to be important in the coupling between the sloshing of the liquid and car motions. The response of the vehicles was increased by the sloshing when the liquid frequency was close to the natural frequency of the vehicle. In addition, the authors found that the stiffness of the suspension springs played an important role in the vehicle response during sloshing. Vehicle accelerations and the displacement of the liquid surface increased as suspensions stiffness increased. The relative amount of surface displacement increased as the liquid depth decreased.

In 1998 researchers from the Ukraine used a detailed mathematical model of a set of pendulums to assess the effects of liquid cargo [11]. Multibody dynamics (MBD) simulations were validated by test data from impact tests and start-up of a six-car consist. Several operational conditions were considered: a single tank car colliding with a loaded freight car, a six-car consist under braking, a six-car consist travelling over tangent track with random irregularities and on a 650 m radius curve. During collisions between a tank car and a loaded freight car, an increase in outage resulted in lower coupler forces, but larger suspension deflections. During braking, sloshing resulted in increased oscillations in the in-train forces of the consist. Larger lateral and vertical accelerations occurred due to sloshing on tangent track with random irregularities and on a 650 m radius curve.

In a 2005 study from Spain [12] a pendulum model was used to study lateral motions and a mass-spring model was used to study longitudinal motions. These models were calibrated using the commercial FEA software ANSYS. The MBD simulations were performed using SIMPACK. MBD simulations of four two-axle tank cars with various fill levels up to 87% did not reveal any safety concerns for an S-curve with a radius of 500 m at 120 km/h or on tangent track with accelerations/braking of up to 1 m/s^2. Under certain scenarios, it was shown that unused coupling screws could come loose from the hanger. The cause was a resonance between the first frequency of the longitudinal sloshing of the lading and the coupling screws.

Iranian researchers performed single vehicle MBD simulations on curved track (250 m radius of curvature) with randomly generated irregularities in 2010 [13]. The MBD simulations were performed with ADAMS software. A spring-mass system was used to model the fluid. Irregularities in elevation, alignment, superelevation, and gauge were generated using Monte Carlo simulations. Due to the oscillatory nature of sloshing induced forces and stresses, it was suggested that sloshing could contribute to fatigue damage of suspensions and connections. Fill ratios of 46% and 85% were considered. Consideration of sloshing in the simulations

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[2] Single-wheel L/V is a key ratio in railway design that relates the lateral force L exerted by a train's wheel on the rail at a given time to the downward force V exerted by the wheel at the same time. High single-wheel L/V ratios are associated with an increased likelihood of wheel-climb derailments.

resulted in an increase of 18% for the single-wheel L/V ratio and an increase of 25% for the wheel unloading ratio[3]. Speeds between 50-65 km/h were considered. Slower speeds led to larger wheel unloading ratios. The authors contended that, in general, the benefit of lowering the centre of gravity of the tank car through a partially filled state outweighed the negative aspects of the oscillatory forces caused by sloshing of the liquid. The results showed that, compared to water, sulphuric acid (which has a higher density and thus greater outage for a given weight limit) had a 13% lower L/V ratio and a 15% lower unloading ratio.

A team from Italy performed simulations of a partially loaded tank car travelling at a constant speed on an S-curve [14] in 2013. A spring-mass equivalent mechanical model was used to model the liquid in MBD simulations, which were conducted using in-house software. ANSYS-Fluent software was used to perform the CFD simulations to determine the parameters of the spring-mass system. The boundary conditions for the simulation were defined by the tank geometry, and only lateral sloshing was considered. Nine equally spaced spring-mass systems were used along the length of the car. The CFD results showed that sloshing response was dominated by the first eigenmode of the liquid, which was dependent on the fill level. The spring-mass EMM was shown to give similar results to the full CFD simulations. The results of the MBD simulations revealed that sloshing caused: greater wheel unloading (up to 20%), increased overturning risk, but no major effect on flange-climb derailments. Fill ratios of 25%, 50%, and 75% were considered.

In 2015 Canadian researchers performed single-vehicle MBD simulations using a single equivalent pendulum extruded along the length of the car body [15], [16]. Universal Mechanism (UM) software was used for the MBD simulations. Only the lateral response was considered. The parameters of the pendulum were calibrated using LS-DYNA. Fill ratios of 46%, 76%, and 97% were analysed for tangent track and curved track. On tangent track, sloshing was found to dampen and reduce hunting. On curved track, an increased unloading of wheels and increased overturning potential were revealed. However, no evidence of increased potential for wheel climb derailments was found.

Also in 2015, Iranian researchers performed modelling and physical testing to explore tank car impacts [17]. The tanks were carried on flatcars using frames. A simple 3-degree-of-freedom (3-DOF) system (consisting of longitudinal translation, vertical translation and pitch) was used to model the vehicle response. Longitudinal sloshing was considered using a separate spring-mass system. LS-DYNA was used to determine the spring-mass system parameters. An ALE approach was used for the FEA. Fill conditions of 50%, 75% and 99% full were considered. Impacts were modelled between two tank cars and between a tank car and a rigid wall at 16 km/h. Sloshing was found to absorb impact energy. The use of the frames was demonstrated to absorb significantly more energy than the case without. Full-scale tests were performed on a stationary tank filled to 50% with water, which was subjected to 3 different forces applied and compared to FEA results and 3-DOF dynamic simulations using a spring-mass EMM. The mass center of displacement was compared for testing, FEA, and EMM. There was excellent agreement between the test data and the FEA. The agreement between the dynamic simulations and test data was reasonable.

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[3] Wheel unloading ratio, $\Delta Q/Q$, is a key ratio in railway design that relates Q, the nominal vertical force that a single wheel places on the rail, with ΔQ, the wheel unloading force (i.e., the change in vertical force). High wheel unloading ratios are associated with an increased likelihood of the railcar rolling over.

A team from the US, Spain, and China developed a novel formulation to improve coupling between MBD and FEA simulations [18] in 2015. This new formulation was called an FE-FFR (finite element-floating frame reference) and it addressed the issue that EMM models cannot accurately capture free surface effects. On tangent track at very high speeds (216 km/h and above) sloshing led to hunting instability. At speeds below this, hunting did not occur. Sloshing was found to cause large spikes in contact forces and greater wheel-rail separations. On curved track at 126 km/h, sloshing affected the load distribution between wheels, and increased viscosity of the lading led to increased stability.

A 2016 report [19] provided a review of some rail related sloshing literature. It was concluded that sloshing could cause braking issues, but this was more of a concern for air brakes than electronically controlled pneumatic (ECP) brakes. Increased rail and wheel wear could also be caused by sloshing. The author concluded that no definitive conclusions have been reached in the literature about the effect of sloshing on the probability of derailments.

In 2017 an improved pendulum model was proposed [60] which used corrective measures to correct for inaccurate pendulum mass based on the model used in [11]. Forces and moments were applied to the carbody to compensate. The model was developed using Universal Mechanism (UM) software. Simulations were performed on tangent track and a curve with a 650 m radius at speeds in the range of 40 – 120 km/h. Four different partial fill levels were considered between 66% and 98%. On the curved track at speeds of 40, 60 and 120 km/h a significant reduction in the “derailing stability margin coefficient”. This is in the potential for derailment was found. The most significant potential for derailment occurred with the partial fill of 66%.

3 REVIEW OF TSB ACCIDENT AND INCIDENT DATA AND A SURVEY OF INDUSTRY EXPERTS

A discussion was held with Transportation Safety Board of Canada (TSB) staff about the issue of railway tank car sloshing. Section 3.1 contains a description of this discussion and the results of a review of the TSB accident report database.

Section 3.2 summarizes the results of interviews and communication with over 15 rail industry experts (typically with 25 or more years of experience) on the subject of railway tank car sloshing. The key questions asked were:

- Has sloshing ever been reported or known to be the cause of a rail accident or incident?
- Is there the potential for sloshing to occur due to partially loaded tank cars?

3.1 Sloshing as the Cause of an Incident or Accident – TSB Data

Discussions were held with TSB staff on the subject of railway tank car sloshing. The TSB staff members said they were not aware of any recent TSB investigations, from the past 15 years, where liquid sloshing was identified and analyzed. However, they recommended that a search of TSB's accident reports be conducted.

Electronic versions of TSB's published accident reports were available from the TSB website for the period from 2000 to 2016. These were searched for key words and phrases that included "sloshing", "Fill Ratio", "Outage", "half-full", "half full", "partially full", "partially fill", and "partial fill".

The search found two reports (R00T0067 [61] and R99T0256 [62]) where the word "sloshing" was found. In TSB Report R00T0067 the word "sloshing" was used as follows:

> "…*are equipped with hydro-damps to reduce the risk of rupture disc failure by reducing the* ***sloshing*** *of the liquid acid*".

In TSB Report R99T0256 the word "sloshing" was used as follows:

> "*As the derailment circumstances were further analyzed, it became apparent that car PROX 81179 was not completely empty and that it contained residual amounts of product. Liquid product* ***sloshed*** *out of the hole in the car during re-railing efforts, displacing the temporary magnetic patch that had to be re-secured with silicone sealant*".

In both of these derailment reports it is apparent that sloshing was not the cause of the derailment.

A subsequent search of the TSB Rail Occurrence Database System (RODS) database revealed four matches for the term "slosh".

1. R00V0013 (Feb 2, 2000) [63] : *"DURING SWITCHING OPERATIONS CN TRANSPORTATION PERSONNEL NOTICED PRODUCT* ***SLOSHING*** *FROM CAR NATX 37815, LOAD OF METHANOL,UN1230. THE CAR WAS LEAKING FROM THE MANWAY COVER AREA. CN SCO RESPONDED AND THE CAR WAS SECURED WITHOUT INCIDENT AT 1400 HRS BY TIGHTENING THE MANWAY COVER BOLTS."*
2. R02H0084 (Feb 13, 2002) [64]: *"WHILE LEAVING CUSTOMER'S SIDING AFTER SPOTTING SAME WITH 2 LOADS THE TRAILING CAR DERAILED L1 AND R3 ON REGULAR BASIS THE*

CREW BRINGS THESE CARS INTO THE CUSTOMER WHILE PERFORMING THEIR SWITCHING IT IS FELT THAT THIS WITH THE ***SLOSHING*** *MOVEME THIS OCCURRENCE WAS ADDED TO RODS FOLLOWING RECENT DISCUSSIONS WITH INDUSTRY REGARDING REPORTING REQUIREMENTS."*

3. R06T0334 (Nov 1, 2006) [65]: *"THE MIDNIGHT YARD ASSIGNMENT NOTICED PRODUCT LEAKING FROM THE TOP OF A DG CAR (GATX 80427 - DIESEL FUEL -UN 1202 CLASS 3). APPROXIMATELY 5 GALLONS WAS FOUND SPREAD OVER SEVERAL LOCATIONS. THE PRODUCT WAS* ***SLOSHING*** *DURING SWITCHING, CAUSING FUEL TO DRIP DOWN SIDES OF CAR AND BOTH SIDE MIDDLE LADDERS. THE DOME SEAL WAS INCORRECTLY POSITIONED. A PAIL WAS POSITIONED TO CATCH DRIPS, AND TOP DOME WAS OPENED, SEAL REPOSITIONED, AND DOME RESECURED."*
4. R06V0272 (Dec 23, 2006) [66]: *"CN REPORTED THAT A YARD EMPLOYEE WAS ADJUSTING BOXED KNUCKLES BETWEEN LOCOMOTIVE CN 7046 AND A TANK CAR WHEN* ***SLOSHING*** *ACTION FROM THE TANK MOVED THE CAR FORWARD PINCHING THE EMPLOYEES RIGHT ARM AND HAND. THE EMPLOYEE WAS AIRLIFTED TO DAWSON CREEK AND HOSPITALIZED FOR 4-6 DAYS WITH UNDETERMINED INJURIES."*

In Items 1 and 3 above, sloshing was reported in reference to spillage or leaking products, not with respect to being the cause of a derailment or injury.

Note that Item 2 above (RODS R02H0084) is quoted exactly as it was written in the TSB report. The word sloshing is in a long run-on sentence, and the thoughts being expressed appear to stop with what appears to be an incomplete form of the word "movement."

Item 2 appears to describe the possible involvement of a sloshing liquid with respect to a yard derailment. This was not investigated, so it is not known if sloshing played a role in this yard derailment or was simply observed to occur due to the derailment or other car movements, and that the derailment was caused by other factors.

In Item 4 above (RODS R06V0272), a worker was injured when a "***sloshing*** *action from the tank moved the car forward."* This is the only instance of sloshing being attributed to a safety related incident.

The potential for sloshing to cause a car to move unexpectedly in yard or switching operations was later confirmed by discussions with an experienced industry expert. He noted that liquid sloshing can cause an uncoupled tank car to move in unexpected ways, as the forces caused by the liquid motion can cause the tank to roll or move in a way that a non-liquid commodity car would not. He noted that this effect was most prominent in switching operations and that when a car is coupled to other cars the draft gear would control these motions and they may not be seen to observers as anything more than a motion of the tank on the rail car suspension, rather a motion of the entire car.

3.2 Potential for Sloshing to Occur – Industry Expert Interviews

Experts from the rail industry (railroads, car manufacturers, shippers, etc.), and from TC, TSB, United States Federal Railroad Administration (FRA), Association of American Railroads (AAR), were consulted on the subject of railway tank car sloshing. The key questions asked were:

- Has sloshing ever been reported or known to be the cause of a rail accident or incident?
- Is there the potential for sloshing to occur due to partially loaded tank cars?

The experts reported that the potential for sloshing to occur is determined by the fill ratio of the tank. A fully loaded tank will have no open space above the liquid line, and the liquid will slosh or move very little. As the fill level decreases the open space increases and the liquid in the tank has more space to move and to form waves. This movement and the wave actions that result have been studied in many research efforts as described in Section 2.

Most experts agreed that for purely economic reasons it was always in the interests of a railroad and a shipper to fill a tank car to its maximum capacity, and to empty a tank as completely as possible. The expected norm for operations is therefore that tanks are in general either ‘full’ or ‘empty’. A typical estimate for the volume transported is between 90% and 95%.

However several experts stated independently that the possibility for partially loaded tanks does exist, and does occur in practice. The reasons given for the existence of partial loads are as follows:

- A buyer orders less than a tank load of a specialty commodity, so a fully loaded tank may then be partially unloaded, or a partially loaded tank is made and shipped. This type of load condition would be a single tank, not a unit-train situation.
- A tank designed for a nominal density commodity is used to ship a similar commodity that is slightly denser. The result is that the weight limit of the tank is reached before the volume limit is. This potential is common with some commodities, where the density can vary depending on the commodity (and temperature). This type of partially loaded tank could occur as a single car or as a unit train.
- A track segment with weight restrictions will place a limit on the weight of cars passing, such that larger volume tanks must be partially loaded to meet this weight restriction. For example, if a tank car designed to have load of 286,000 lb capacity when filled to a 98% fill ratio is to be routed over a section of track with a 263,000 lb limit, this car would need to be filled with less than 98% volume to reach the load limit. This type of partial load may be more common than the first two listed above, and may occur as single cars or as unit trains.

One industry expert stated that cars are typically underfilled by 2% to 5%. However, this can be by either mass or volume. If it is by mass, then the volume fill ratio is typically about 85%, but if it is by volume, then it is typically 95% to 98%. The determining factor on whether the car is filled by mass or by volume is the density of the product going into the tank car. This means that some shippers will almost always fill by mass and others will almost always fill by volume depending on what they are shipping. Although different tank cars are designed for different commodities, or at least different groups of commodities, there is still some significant variation in the density. For example, the density of oil is quite different depending on where it is coming from. It was estimated that if a shipping company used about 1,000 cars in its fleet, there would likely be 2 to 5 cars a year that would be underfilled by 25% to 50%.

The general understanding within the industry is that because the tank is filled to a lower volume level, the overall centre of gravity of the tank is lower (and it will be below the allowed maximum CG height) and therefore the chance of tipping in low speed curves or lifting a wheel at higher speeds is reduced. The reasoning is that per design regulations, a loaded car cannot have a center of gravity exceeding 98 inches above the top of the rail. A partially filled car, even if filled to the maximum load allowed, would have to have a lower center of gravity and therefore be more difficult to tip. A partially loaded tank, that is under the design load limit (for example, loaded to 263,000 lb) would be both lower in weight and have a lower center of gravity, both helping to make the partially filled car less susceptible to tipping (under static conditions).

None of the experts interviewed knew of an instance where an underfilled tank car had caused a safety issue or a concern.

In other interviews with industry experts, including an experienced locomotive engineer, it was acknowledged that a unit train of liquid commodity can be ‘felt’ by the locomotive engineer when in operation, and that all experienced operators expect this longitudinal dynamic motion effect to be felt on some unit trains. However, it was also communicated that the fact that an engineer can feel or sense the motion of the locomotive due to train dynamics does not mean that they thought these forces or motions are dangerous or could cause an accident, but that these motions are common or typical and well known within the industry.

One respondent, with more than 40 years’ experience in the rail industry, working with tank cars for most of that time, had just completed an over-the-road test of a tank car filled with water. In several thousand miles of testing (with load measuring instrumentation on the tank car) he reported that an unsafe condition was not measured during the entire testing period.

In summary, the industry experts advised that:

- sloshing of liquids within a rail tank car has never been attributed as the cause of a derailment or a mainline accident. (This does not mean that sloshing has not ever been the cause of a derailment, only that it has not to date been attributed as being the cause of a derailment.);
- sloshing does occur during yard and switching operations, where the sloshing forces may cause a car to move unexpectedly. There is one reported injury related to this type of sloshing action during a yard operation;
- sloshing forces do cause train action motions that locomotive engineers have noted; and
- tank cars can be partially filled as part of regular shipping operations, and this may occur in single cars or in several cars in a unit train consist.

4 DYNAMIC SIMULATIONS

4.1 Introduction

Analytical work was conducted to study if movement of liquid in a tank car could contribute to derailments of trains carrying liquid dangerous goods and to determine if there is sufficient evidence to support further investigation into sloshing, such as but not limited to physical testing, Finite Element Analysis and detailed evaluation of the effects of fill ratio and commodity type on rail safety.

A pendulum model was developed to simulate the effect of liquid sloshing in railway tank cars with formulas generated based on Finite Element Analysis data. The liquid sloshing model was then incorporated into the empty tank car MBD model that NRC developed and validated previously with test data from Instrumented Wheelset (IWS) measurements. A spring-mass model of liquid sloshing was also built and integrated into the empty tank car model, and that confirmed predictions made by the pendulum model

Hundreds of thousands of dynamic simulations were conducted for the tank car with liquid cargo at various fill ratios and with an equivalent solid (i.e., rigid) cargo on more than 1,000 measured curves. The conditions under which tank car sloshing could have a detrimental effect on rail transportation safety were identified and evaluated.

4.2 Empty Tank Car Dynamic Simulation Model

The National Research Council Canada (NRC) worked with Transport Canada (TC), the Federal Railroad Administration (FRA), Canadian Pacific Railway (CP), and Canadian National Railway (CN) between 2009 and 2012 to study the impact of curvature on track geometry safety standards [67] [68]. Testing was conducted on more than 523 miles of track with 1,340 curves on four subdivisions of CN and CP main track between Vancouver and Kamloops, British Columbia as shown in Figure 4-1.

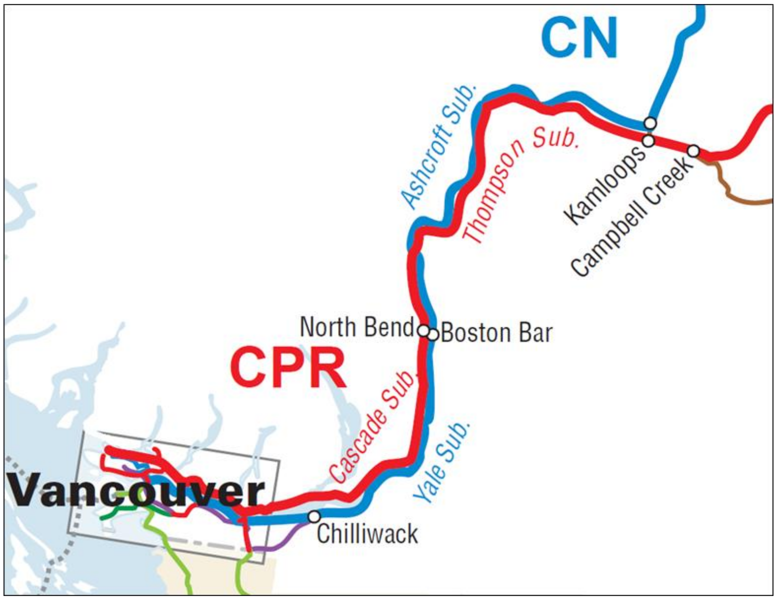

Figure 4-1: Test track.

The curvature distribution is shown in Figure 4-2. While the majority of the curves were between 2° and 8°, 18 very sharp curves of greater than 10° were encountered. The curvature of the sharpest curve is about 11.4°.

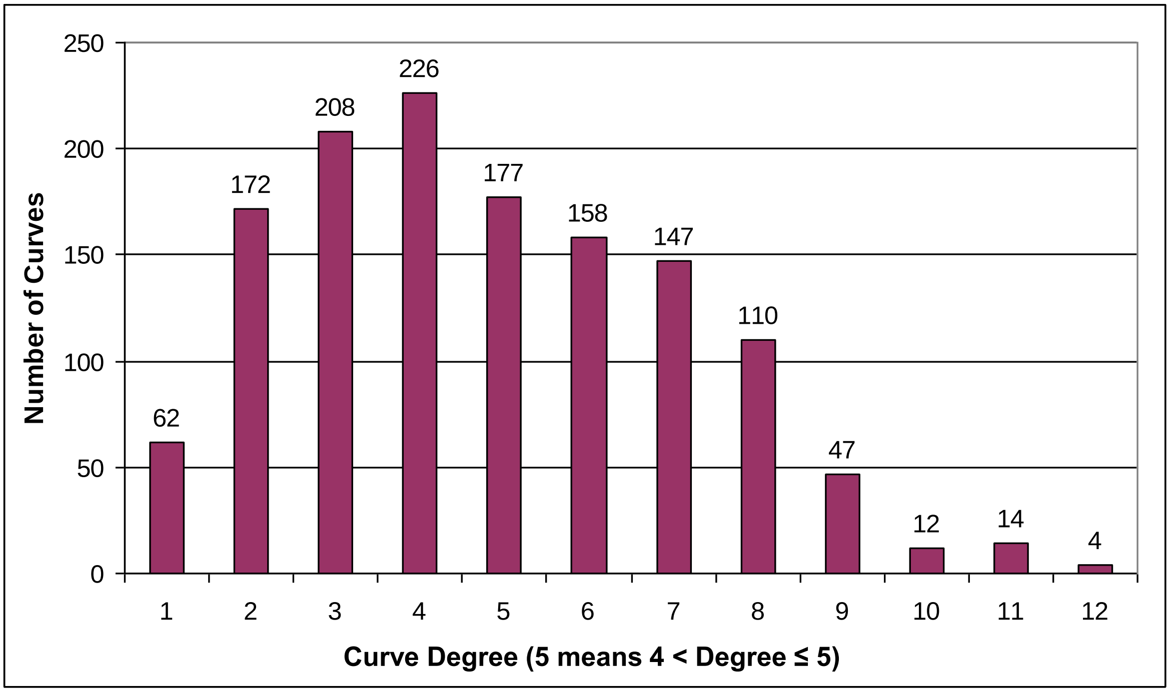

Figure 4-2 New Distribution of curvature for test track.

An empty tank car (IC400031) with a tare weight of 59,800 lb was equipped with instrumentation to measure car performance during field testing. The car was designed with a gross rail load (GRL) of 263,000 lb, but did not operate in this condition during the field tests. The car was equipped with two instrumented wheelsets (IWSs) as shown in Figure 4-3 to measure vertical, lateral and longitudinal wheel-rail interaction forces during testing, along with accelerometers, gyroscopic pitch and roll transducers, and displacement transducers.

Figure 4-3: Instrumented tank car.

Some key information for the tank car is listed in Table 4-1.

Table 4-1: Tank car information.

Car Number	IC400031	
Gross Rail Load	263,000	lb
Tare Weight	59,800	lb
Load Limit	203,200	lb
Gallonage Capacity	20,738	US gal
Car Length	52’10”	
Outside Extreme Width	10’1”	
Outside Extreme Height	14’6”	
Truck Center Length	37’10”	
Coupler Length	28.5”	

A computer simulation model of the dynamic behaviour of the empty tank car was developed using VAMPIRE, a commercial software package that is widely used for rail vehicle dynamics simulation.

The vehicle model in the simulation incorporates a rigid car body mass, bolster masses, and side frame and axle masses. These are accompanied by models for the centre plate, constant contact side bearings, secondary truck suspension with springs and friction wedges, bearing adapter pads, axles and wheels. The vehicle model also includes eight separate wheel profiles that were measured on the car under test.

The VAMPIRE model was used to generate time-history data (wheel forces vs. time) as the rail cars travelled along simulated track with the same geometry as that measured in the field tests. The simulation results were compared with field test measurements. The comparison of measured and simulated time histories of wheel forces showed that the vehicle and track model developed can simulate car performance in curves with a high degree of fidelity. Good agreement between simulation and field test results was achieved for dynamic wheel-rail forces on different curves. It was shown that the computer model can accurately reproduce the responses of the car to track geometry variations on curved track. The model can also accurately predict the car responses over a given track geometry when operational speed and wheel-rail surface conditions are changed [67].

For comparison purposes, a solid-payload tank car simulation model was developed by taking the validated empty tank car model and adding a non-moving payload located in the bottom of the tank.

The validated empty tank car model, the solid-payload model and the liquid sloshing simulation model were all used to study the effects of tank car sloshing on rail transportation safety.

For the purposes of this study, the liquid in the tank was assumed to have a density of 1,000 kg/m^3. This is the upper limit of the range of densities given by the American Petroleum Institute (API) for heavy crude oil (920 -1,000 kg/m^3). The effects of other densities were not studied.

4.3 Tank Car Liquid Sloshing Simulation Model

A trammel pendulum has been used in many studies to simulate the lateral motion of the fluid in partially filled elliptical tankers [16] [15] [23] [30]. The equations used in these studies apply to elliptical tankers with various different aspect ratios. Most, if not all, of the railway tankers are cylindrical in shape. Therefore, in this study, pendulum model equations for cylinder-shaped tank cars were developed based on FEA data which are more accurate than the equations applicable to various aspect ratios.

A pendulum model for a railway tank car with sloshing liquid is shown in Figure 4-4. The red line in the figure shows the liquid fill level when the tank is stationary. The fluid mass is divided into two portions: a fixed portion M_f; and a moving (pendulum) portion M_p. with a pendulum length L. The pendulum pivot is located at the centre of the tank so it can most effectively model the overall sloshing of the liquid. A list of the pendulum model parameters is shown in Table 4-2.

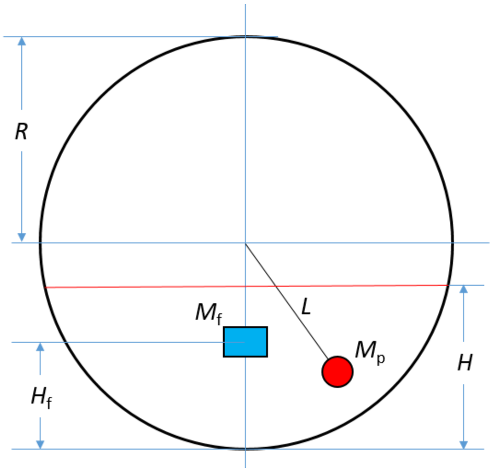

Figure 4-4: Pendulum model for railway tank car.

Table 4-2: Pendulum model parameters.

Symbol	Description
M_f	Fixed mass of liquid
M_p	Pendulum mass of liquid
M_t	Total liquid mass
R	Tank radius
L	Pendulum length
H	Liquid fill level from tank bottom
H_f	Height of fixed mass of liquid from tank bottom
H_t	Height of center of gravity of total liquid from tank bottom
δ	Fill ratio
ε	Pendulum mass ratio
μ	Pendulum length ratio
λ	Fixed mass height ratio

Fill ratio δ is defined as the ratio of the height of the liquid fill level above the tank bottom over the inside diameter of the tank, which can be expressed as

$$\delta = \frac{H}{2R} \tag{4-1}$$

where *H* is the liquid fill level from the tank bottom and *R* is the tank radius.

Outage is a term commonly used in the gauging of tank cars, which can be either in units of length or percentage. When it is in units of length, it is defined as the unfilled portion of the tank car measured from the inside top of the tank shell down to the level of the liquid. When it is in the unit of percentage, it is defined as the unfilled volume of the tank over the full volume of the tank. The relationship between outage and fill ratio is shown in Figure 4-5. At fill ratios of 50%, 60%, 70% and 80%, the outages are 50%, 37%, 25% and 14%, respectively.

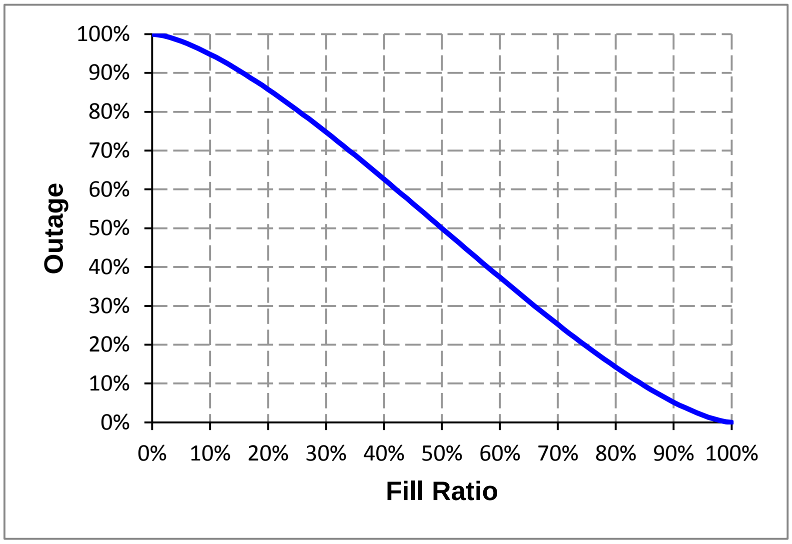

Figure 4-5: Outage versus fill ratio.

Pendulum length ratio μ is the ratio of pendulum length over tank radius which can be expressed as

$$\mu = \frac{L}{R} \tag{4-2}$$

The relationship between pendulum length ratio and fill ratio is shown in Figure 4-6. The red points represent the results obtained from Finite Element Analysis results of natural frequencies of fluid oscillation at fill ratios between 5% and 90% [23]. The two blue points were added so that the generated equation would cover fill ratios from 0% to 100%.

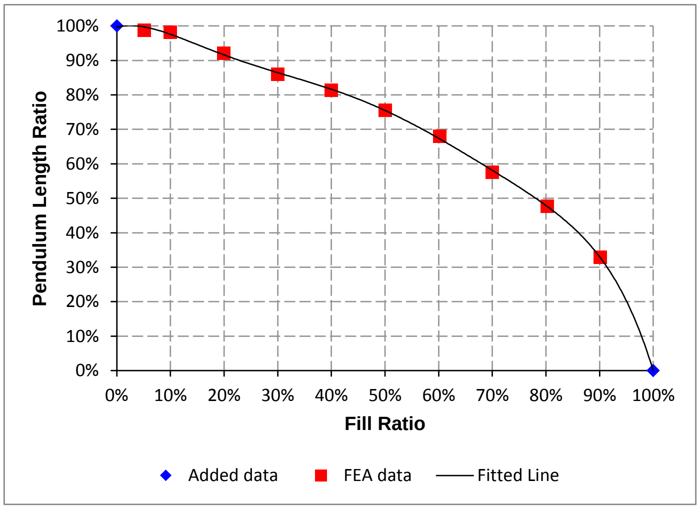

Figure 4-6 Pendulum length ratio versus fill ratio.

The following pendulum length ratio equation was generated based on the data shown in Figure 4-6:

$$\mu = -27.207\delta^6 + 75.514\delta^5 - 79.945\delta^4 + 39.526\delta^3 - 9.2865\delta^2 + 0.4029\delta + 0.9961 \qquad (4\text{-}3)$$

The fitted line in Figure 4-6 was based on Equation (4-3).

Pendulum mass ratio ε is the ratio of pendulum mass of liquid over total mass of liquid, which can be expressed as

$$\varepsilon = \frac{M_p}{M_t} \qquad (4\text{-}4)$$

where M_p is pendulum mass of liquid and M_t is total mass of liquid which is equal to the sum of fixed mass of liquid and pendulum mass of liquid.

The relationship between pendulum mass ratio and fill ratio is shown in Figure 4-7. The red points represent the results obtained from Finite Element Analysis results of maximum horizontal component of sloshing force per unit liquid weight at fill ratios between 10% and 90% [23]. Similar to the case in Figure 4-6, two blue points were added.

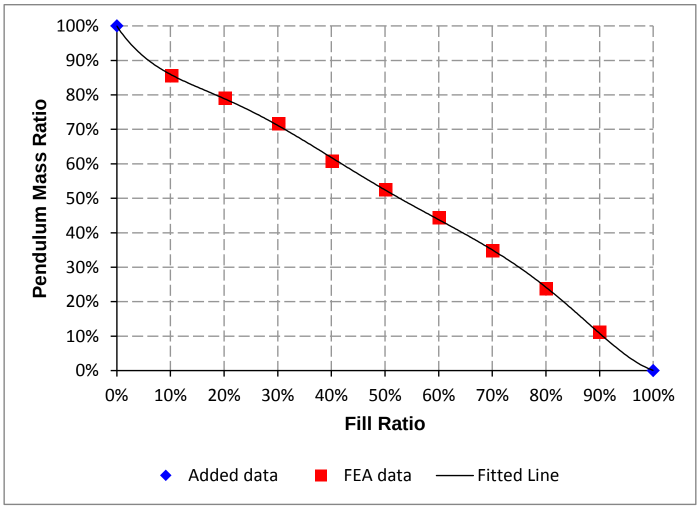

Figure 4-7: Pendulum mass ratio versus fill ratio.

The following equation for pendulum mass ratio was generated based on the data shown in Figure 4-7:

$$\varepsilon = 24.897\delta^6 - 76.387\delta^5 + 89.137\delta^4 - 49.512\delta^3 + 13.169\delta^2 - 2.3024\delta + 0.9994 \quad (4\text{-}5)$$

The fitted line in Figure 4-7 was based on Equation (4-5).

Fixed mass height ratio λ is the ratio of the height of the fixed mass of liquid over the tank radius which can be expressed as

$$\lambda = \frac{H_f}{R} \quad (4\text{-}6)$$

The center of gravity (CG) of the fixed mass and the pendulum mass should coincide with the CG of the total fluid. Taking the mass moment around the tank bottom gives:

$$M_f H_f + M_p(R - L) = M_t H_t \quad (4\text{-}7)$$

The following equation for the fixed mass height ratio λ can then be obtained from Equations (4-2), (4-4) and (4-7):

$$\lambda = \frac{H_t - \varepsilon R(1-\mu)}{R(1-\varepsilon)} \quad (4\text{-}8)$$

4.4 Lateral In-Train Force

To evaluate the effect of tank car sloshing on rail safety under an in-train force condition, dynamic simulations were performed on a tank car subjected to a gradually increasing in-train force such as a buff force. Under buff force and high cant deficiency conditions, the lateral component of the in-train force increases the car rollover risk.

A sketch for a car under buff condition is shown in Figure 4-8. The lateral component F_y of the in-train force F can be expressed by

$$F_y = F \times \sin\emptyset \tag{4-9}$$

where:

F = In-train force

F_y = Lateral component of in-train force

$\emptyset$ = Coupler angle

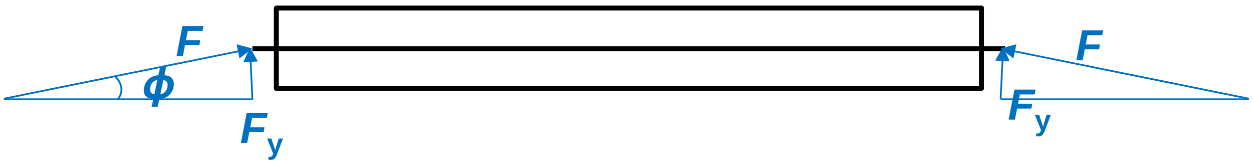

Figure 4-8: Lateral in-train force under buff condition.

Coupler angle $\emptyset_1$ for a car (referred to as car 1 hereinafter) in connection with another car (referred to as car 2 hereinafter) under same direction of buff forces at two ends can be expressed as:

$$\emptyset_1 = 180 - \mathrm{atan}\left(\frac{\sqrt{R^2 - \frac{A_1^2}{4}}}{\frac{L_1}{2} - C_1}\right) - \mathrm{acos}\left[\frac{(C_1+C_2)^2 + \left(\frac{L_1}{2} - C_1\right)^2 - \frac{A_1^2}{4} - \left(\frac{L_2}{2} - C_2\right)^2 + \frac{A_2^2}{4}}{2(C_1+C_2)\sqrt{\left(\frac{L_1}{2} - C_1\right)^2 + R^2 - \frac{A_1^2}{4}}}\right] \tag{4-10}$$

where:

$\emptyset_1$ = Coupler angle for car 1 (deg)
R = Radius of curve (ft)
A_1, A_2 = Truck center distance[4] for car 1 and car 2 (ft)
L_1, L_2 = Length over pulling faces of couplers[5] for car 1 and car 2 (ft)
C_1, C_2 = Coupler length[6] for car 1 and car 2 (ft)

Hundreds of thousands of dynamic simulations were conducted for the tank car with liquid cargo at fill ratios of 80%, 70%, 60% and 50% and with equivalent solid cargo under various in-train force conditions on more than 1,000 measured curves. The simulation results show that tank car sloshing has a much higher impact on wheel unloading than on wheel climbing. Therefore,

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[4] Truck centre distance is the longitudinal distance between the centres of the two trucks on a rail car.

[5] Length over the pulling faces of the couplers for a car is the increase in train length that occurs when the car is added to the middle of a train and a light draft force is applied.

[6] Coupler length is the length of a coupler from the pulling face of the coupler to the point where the coupler is allowed to yaw (i.e., rotate about a vertical axis) relative to the car body. This yawing occurs close to the horizontal yoke pin on an AAR Type E coupler, and close to the vertical draft key on an AAR Type F coupler.

the wheel unloading ratio (see Footnote 3 on page 11) was used in this study as a safety measurement to analyze the impact of tank car sloshing on rail transportation safety.

4.5 Effect of Tank Car Sloshing Without In-Train Force

First, the effects of liquid sloshing on tank car safety without in-train forces on the testing curves were analyzed. Figure 4-9 shows simulation results of wheel unloading ratio versus cant deficiency at 80% fill ratio (14% outage). In the left figure, simulated wheel unloading ratios from the liquid model and the solid-payload model are shown in red and blue, respectively. The right figure shows the differences between wheel unlading ratios from the liquid model and the solid payload model.

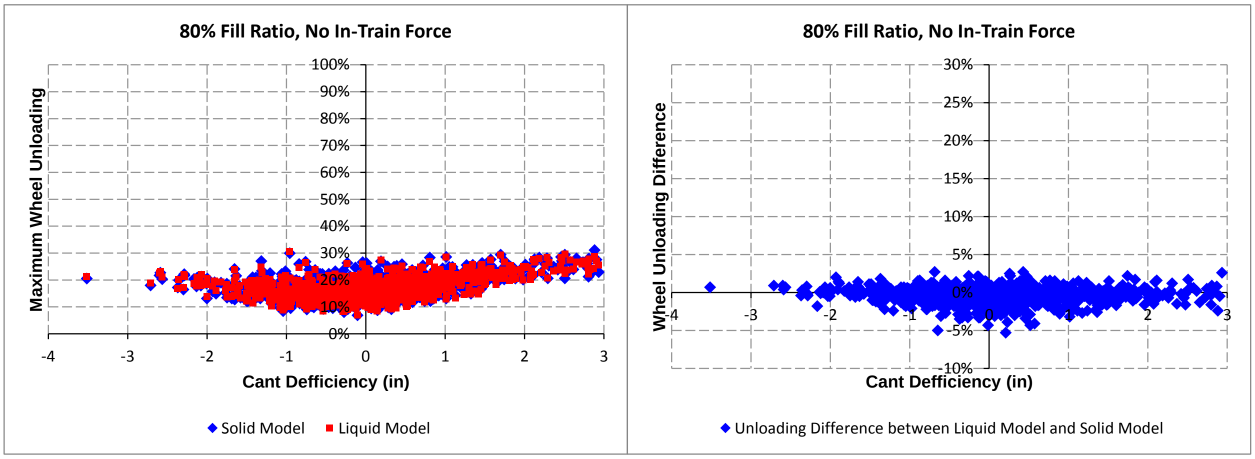

Figure 4-9: Wheel unloading versus cant deficiency at 80% fill ratio and zero in-train force.

Figure 4-10 shows histograms of the wheel unloading ratios from the liquid and solid models and the difference between the wheel unloading ratios from the two models at 80% fill ratio.

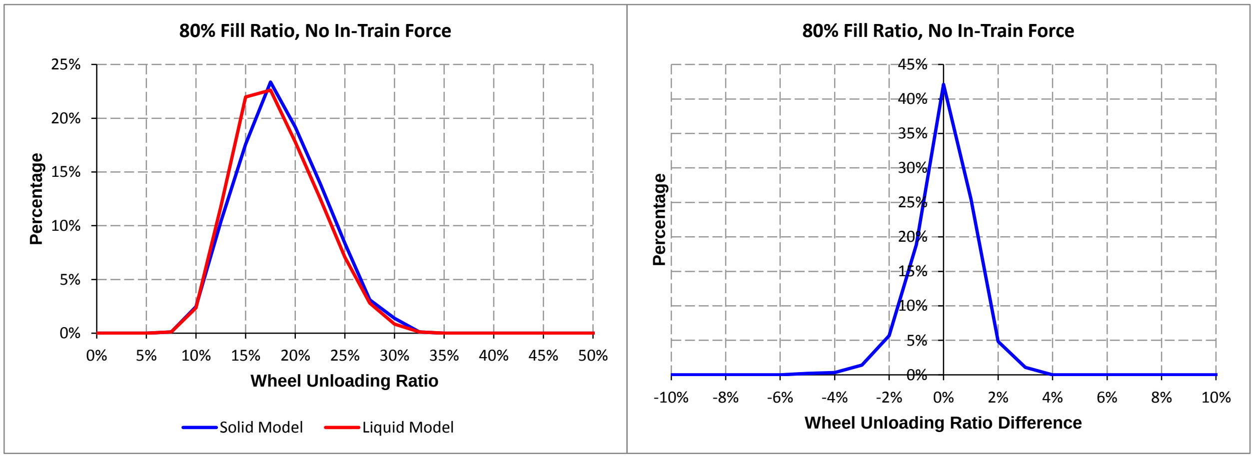

Figure 4-10: Wheel unloading histograms at 80% fill ratio and zero in-train force.

It can be seen from Figure 4-9 and Figure 4-10 that most of the wheel unloading ratios are between 15% and 20%, all of them are less than 35%, and the differences between the maximum wheel unloading ratios from the liquid model and those from the solid model are less than 5%.

Positive cant deficiency exists when a train is travelling through a curve faster than the balance speed, and thus produces a net lateral force to the outside of the curve. It is measured in inches in North America and is the amount of additional superelevation (lifting of the outside rail above the inside one) that would need to be added to achieve balance at the given speed.

The no-in-train-force simulation results of wheel unloading ratio versus cant deficiency at 70%, 60% and 50% fill ratios are shown in Figure A.13, Figure A.22 and Figure A.30 in Appendix A. The histograms of wheel unloading at 70%, 60%, 50% fill ratios are shown in Figure 4-11, Figure 4-12 and Figure 4-13, respectively. It can be seen that maximum wheel unloading ratio differences between the liquid model and solid model for all of the fill ratios at zero in-train force are less than 5%. It should be noted that maximum wheel unloading ratio differences could be as high as 8% for the cases with cant deficiency between 3 and 4 inches. Only cases with cant deficiency lower than or equal to 3 inches, which is the cant deficiency limit in Canada, were used in all the plots in this report. During the testing runs, the cant deficiencies on some of the 1,340 curves were over 3 inches. These cases were studied, but the results were not included in this report.

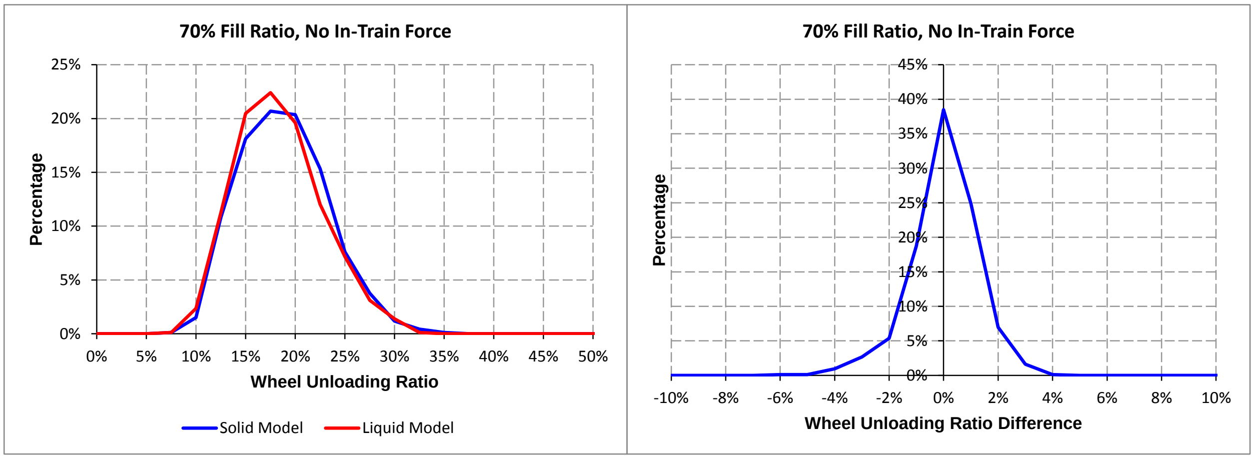

Figure 4-11: Wheel unloading histogram at 70% fill ratio and zero in-train force.

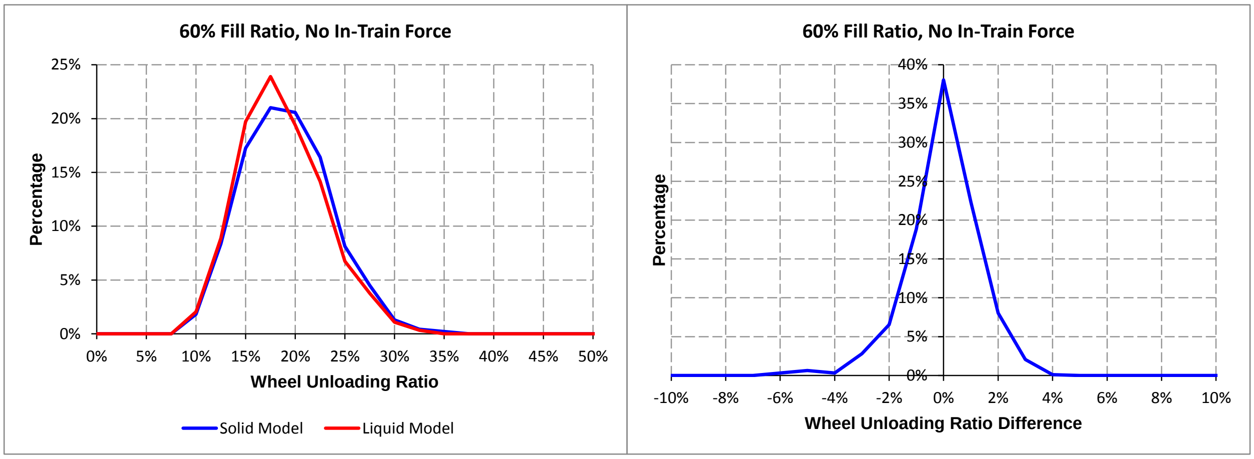

Figure 4-12: Wheel unloading histogram at 60% fill ratio and zero in-train force.

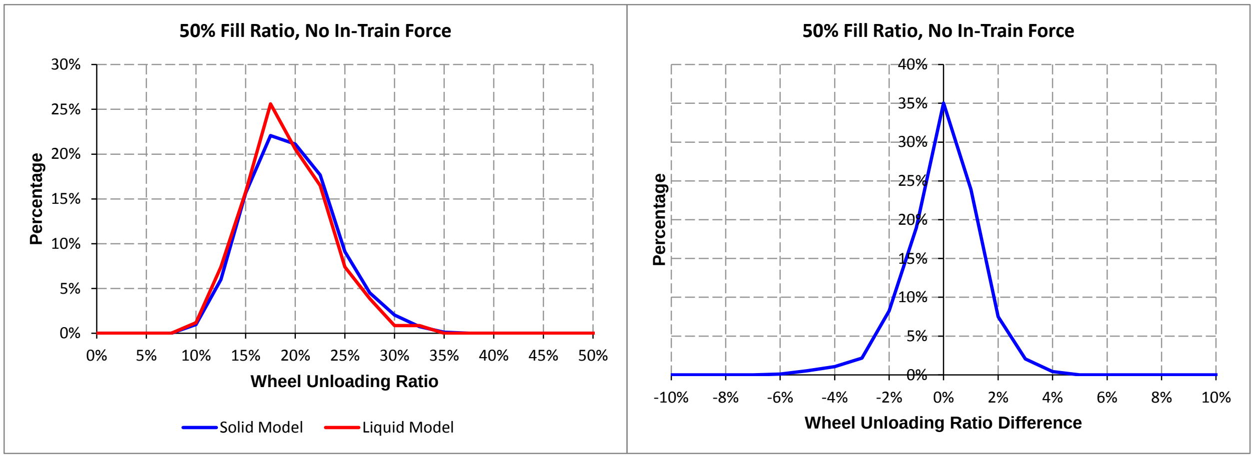

Figure 4-13: Wheel unloading histogram at 50% fill ratio and zero in-train force.

4.6 Effect of Cant Deficiency

The effect of tank car sloshing on wheel unloading is much higher at high lateral in-train forces than that when the lateral in-train force is zero. Figure 4-14 shows wheel unloading versus cant deficiency for the tank car at 80% fill ratio under a 20-kip lateral in-train force. It can be seen that the increase of wheel unloading due to sloshing could be as high as 30%.

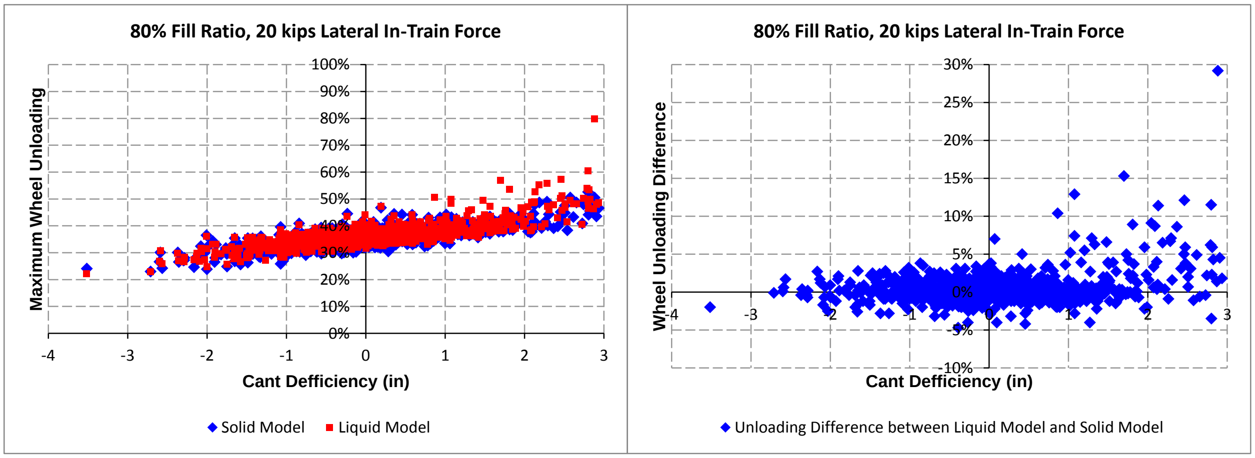

Figure 4-14: Wheel unloading versus cant deficiency at 80% fill ratio and 20 kip lateral in-train force.

As shown in Figure 4-14, the general trend of the effect of tank car sloshing on wheel unloading is that wheel unloading increases with cant deficiency. As noted previously, positive cant deficiency means a car goes through a curve faster than the balance speed and a net lateral force to the outside of the curve is produced. Cant deficiency can be calculated as follows:

$$\text{Cant deficiency} = 0.0007 \times \text{Curvature} \times \text{Speed}^2 - \text{Superelevation} \qquad (4\text{-}11)$$

where cant deficiency is in inches, curvature in degrees, speed in miles per hour, and superelevation in inches.

The effects of tank car sloshing at different ranges of cant deficiency are illustrated with reverse cumulative percentage plots. Figure 4-15 shows the reverse cumulative percentages for wheel unloading ratio and wheel unloading ratio difference at cant deficiencies between 0 and 1 inch. Two points are used to illustrate the meaning of reverse cumulative percentage. Point A in the left graph in Figure 4-15 shows that 40% of the cases have wheel unloading ratios higher than 38%. Point B in the right graph shows that 0% of the cases have wheel unloading ratio differences higher than 5%. The results in Figure 4-15 thus show that the effect of tank sloshing on wheel unloading is small at low levels of cant deficiency.

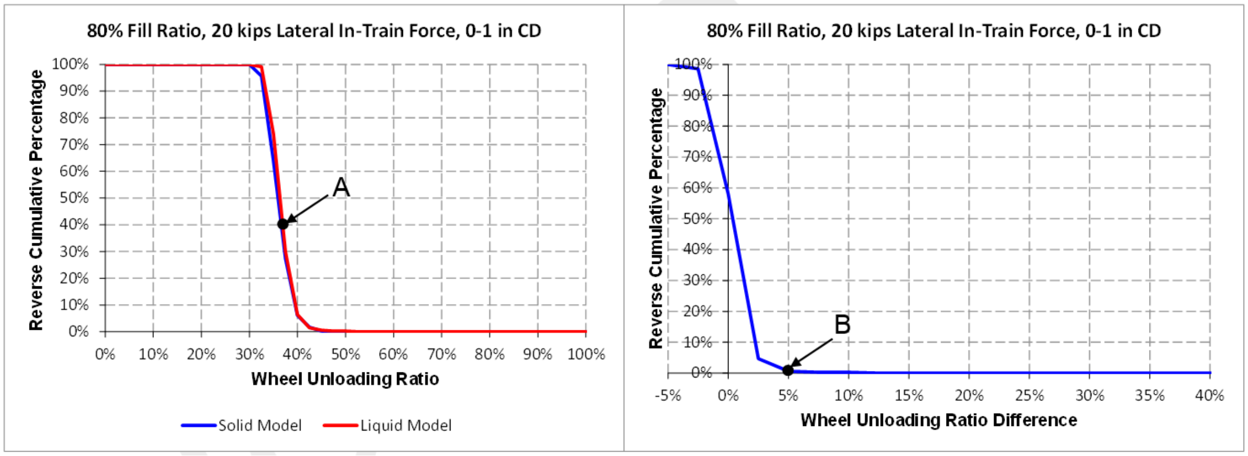

Figure 4-15: Reverse cumulative percentage for wheel unloading ratio and wheel unloading ratio difference at 80% fill ratio, 20 kip lateral in-train force and cant deficiencies between 0 and 1 in.

Figure 4-16 and Figure 4-17 show the reverse cumulative percentages at 1 to 2 inches of cant deficiency and 2 to 3 inches of cant deficiency, respectively. The differences between wheel unloading predicted by the liquid model and the solid model are higher at 2 to 3 inches of cant deficiency than those at 1 to 2 inches of cant deficiency. Those, in turn, are higher than the predictions of wheel unloading at 0 to 1 inch of cant deficiency.

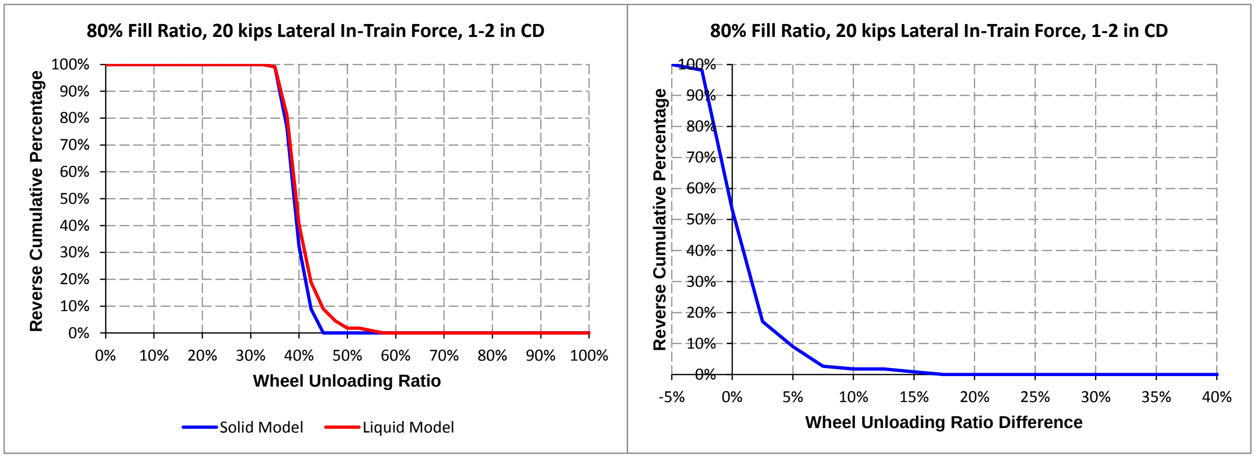

Figure 4-16: Reverse cumulative percentage for wheel unloading ratio and wheel unloading ratio difference at 80% fill ratio, 20 kip lateral in-train force and cant deficiencies between 1 and 2 in.

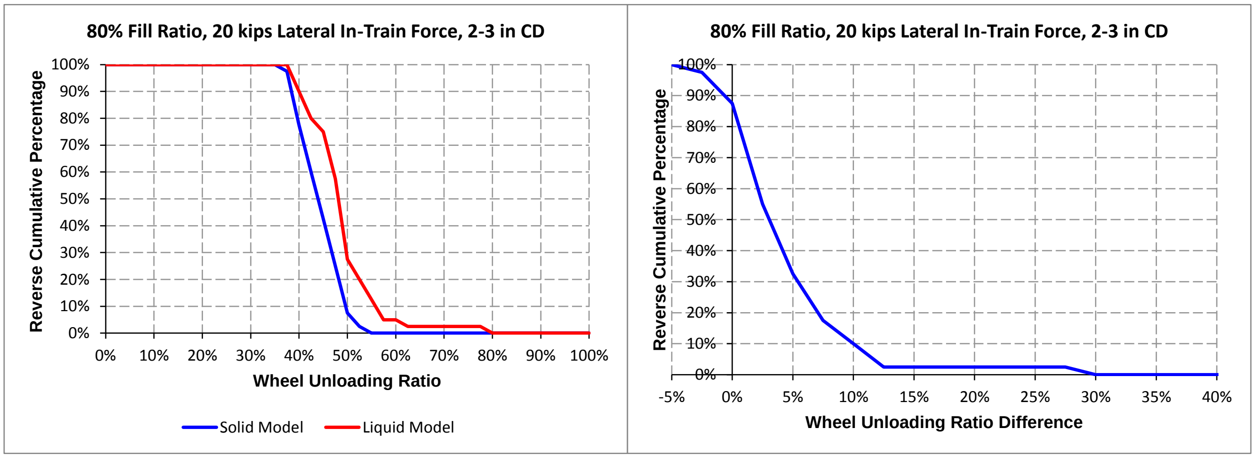

Figure 4-17: Reverse cumulative percentage for wheel unloading ratio and wheel unloading ratio difference at 80% fill ratio, 20 kip lateral in-train force and cant deficiencies between 2 and 3 in.

Reverse cumulative percentages for 0 to 1, 1 to 2 and 2 to 3 inches of cant deficiency for wheel unloading are compared in Figure 4-18. The results clearly show that the effect of tank car sloshing increases as cant deficiency increases.

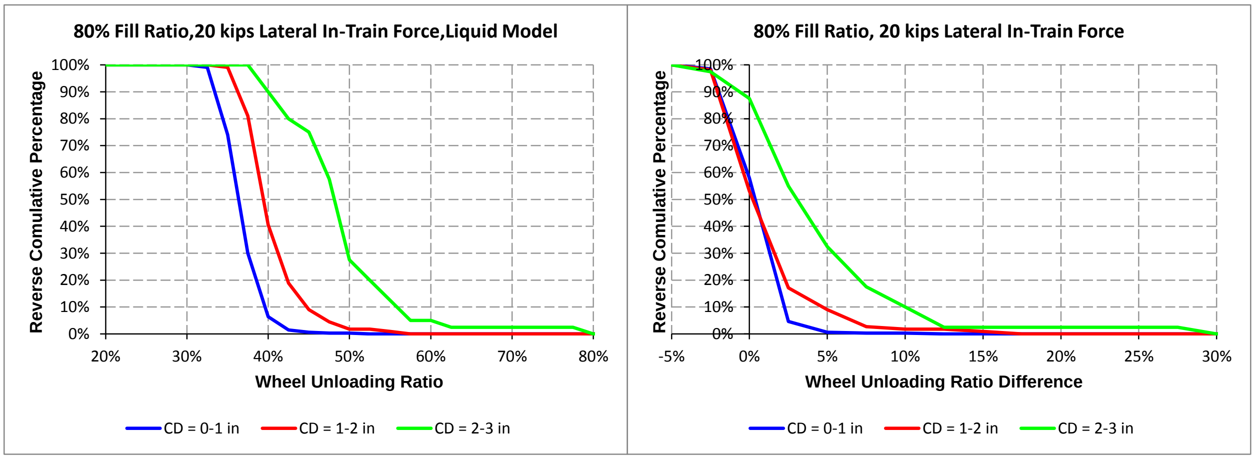

Figure 4-18: Reverse cumulative percentage for wheel unloading ratio and wheel unloading ratio differences at 80% fill ratio, 20 kip lateral in-train force and three ranges of cant deficiency.

Reverse cumulative percentages at the three ranges of cant deficiency for wheel unloading at 70%, 60% and 50% fill ratios are compared in Figure 4-19, Figure 4-20 and Figure 4-21, respectively. They also show that the effect of tank car sloshing increases as cant deficiency increases.

The three figures show that the largest wheel unloading ratio difference is about 35%, and it occurs in the case where there was a 70% fill ratio, 2 to 3 inches of cant deficiency, and a 17 kip lateral in-train force. Thus, if a solid model were used to estimate the wheel unloading instead of a liquid sloshing model, for some combinations of curve, speed and grade the wheel unloading would be underestimated by 35 percentage points (i.e., the wheel unloading ratio would be estimated to be 45% instead of 80%).

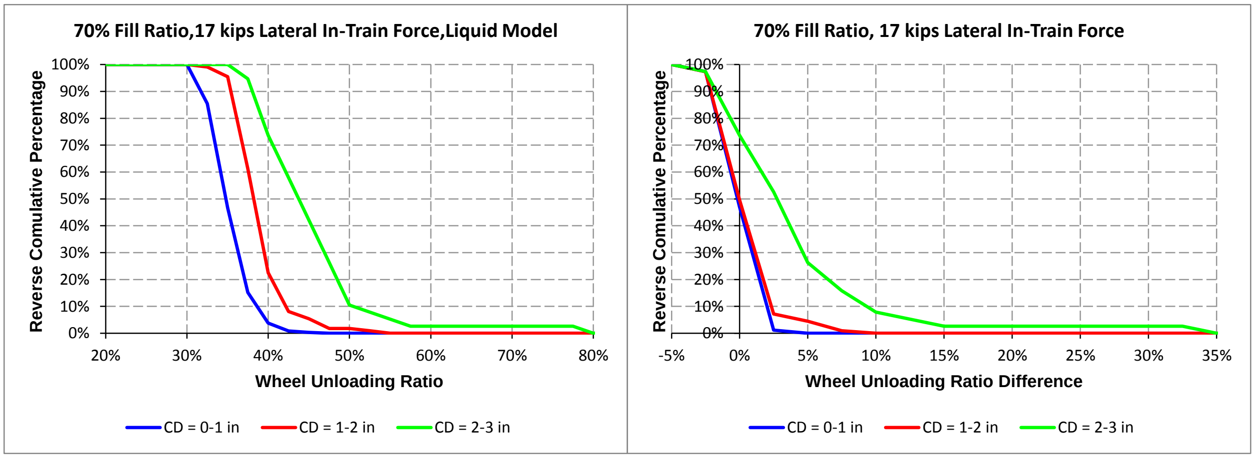

Figure 4-19: Reverse cumulative percentage for wheel unloading ratio and wheel unloading ratio difference at 70% fill ratio, 17 kip lateral in-train force and three ranges of cant deficiency.

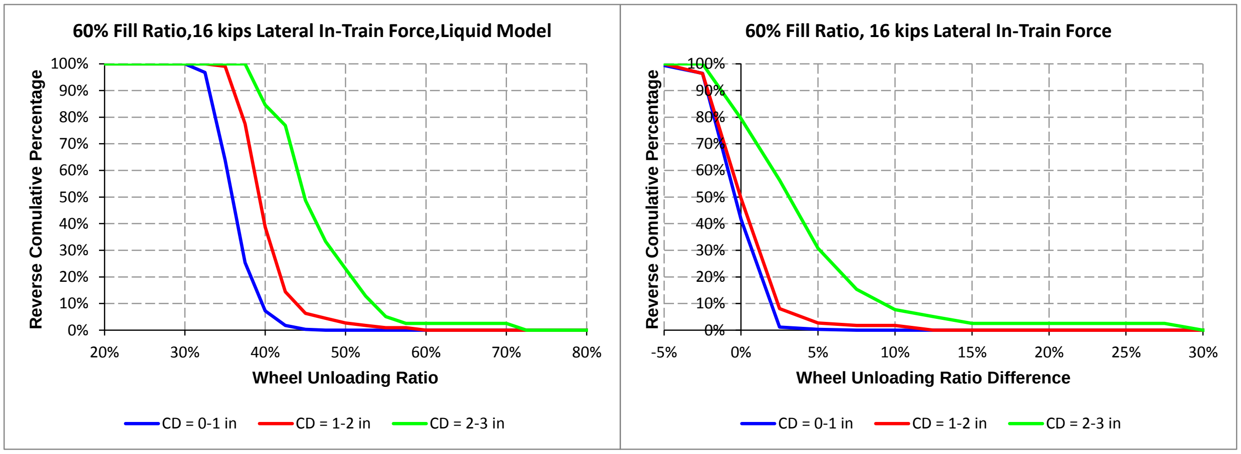

Figure 4-20: Reverse cumulative percentage for wheel unloading ratio and wheel unloading ratio difference at 60% fill ratio, 16 kip lateral in-train force and three ranges of cant deficiency.

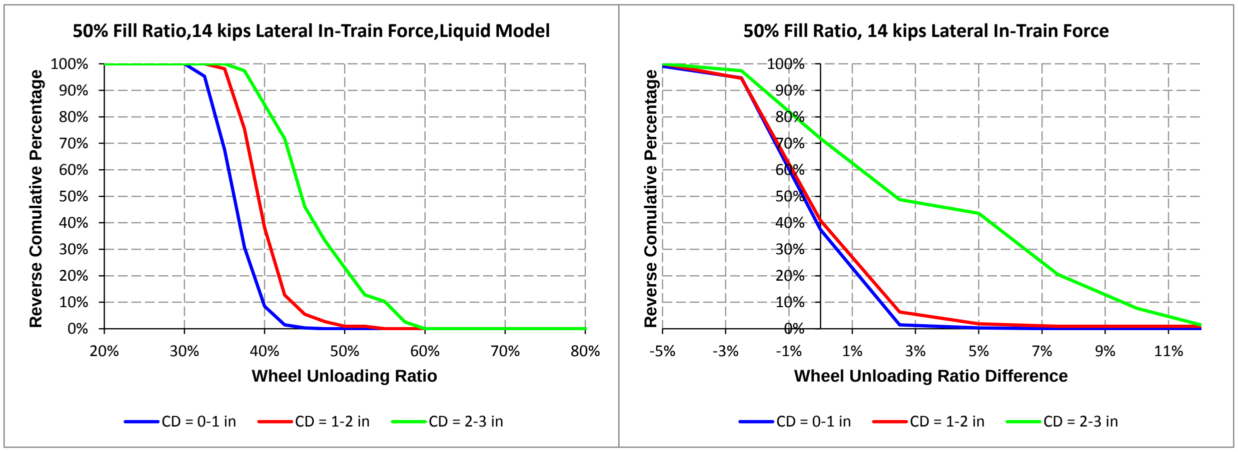

Figure 4-21 Reverse cumulative percentage for wheel unloading ratio and wheel unloading ratio difference at 50% fill ratio, 14 kip lateral in-train force and three ranges of cant deficiency.

As the effect of tank car sloshing on wheel unloading at cant deficiencies lower than 1 inch is very small, the results at cant deficiencies between 1 and 3 inches will be used in the analysis of the effect of tank car sloshing in the following sections. The reverse cumulative percentages for wheel unloading ratio and wheel unloading ratio difference at 80%, 70%, 60% and 50% fill ratios and various lateral in-train forces at 1 to 3 inches of cant deficiency are included in Appendix B.

4.7 Effect of In-Train Force

Reverse cumulative percentages for wheel unloading ratio and wheel unloading ratio difference at 80% fill ratio and lateral in-train forces of 10, 13, 18 and 20 kip are compared in Figure 4-22. The results show that the effect of tank car sloshing increases as lateral in-train force increases. With a 10 kip lateral in-train force, the maximum effect of tank car sloshing is about 5%. At 20 kip lateral in-train force, the maximum effect of tank car sloshing is about 30%.

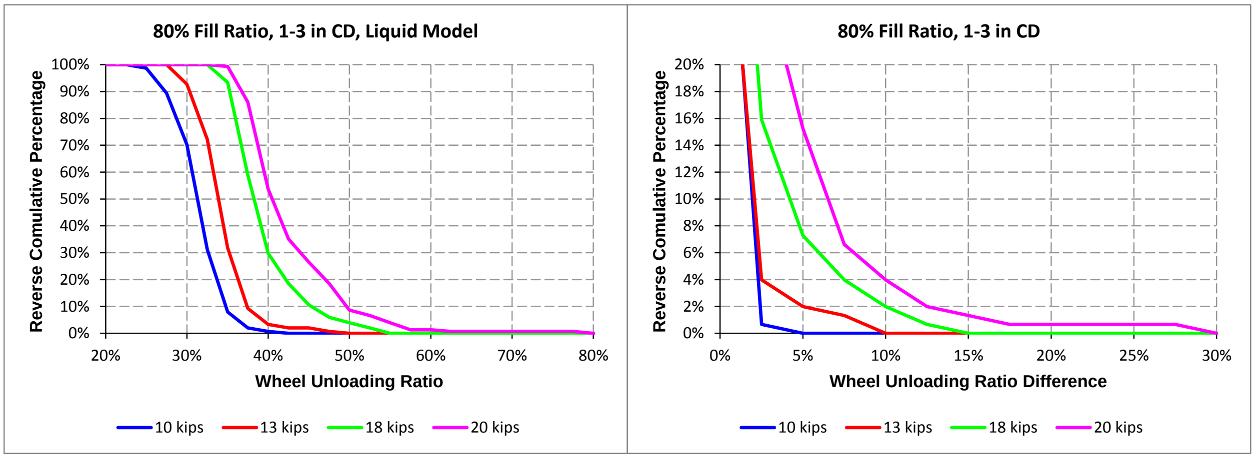

Figure 4-22: Reverse cumulative percentage for wheel unloading ratio and wheel unloading ratio difference at 80% fill ratio and lateral in-train forces from 10 to 20 kip.

The effects of lateral in-train force on wheel unloading ratio and wheel unloading ratio differences for 70%, 60% and 50% fill ratios are shown in Figure 4-23, Figure 4-24 and Figure 4-25, respectively. Similar to the results for 80% fill ratio, the results show that the effect of tank car sloshing increases as lateral in-train force increases.

It should be noted that, to have the same percentage effect of tank car sloshing on wheel unloading, the lateral in-train force needed is lower at lower fill ratios than that at higher fill ratios. The effect of fill ratio on wheel unloading ratio is analyzed in the next section.

The three figures show that the largest wheel unloading ratio difference is about 35%, and it occurs in the case where there was a 70% fill ratio, 1 to 3 inches of cant deficiency, and a 17 kip lateral in-train force. Thus, if a solid model were used to estimate the wheel unloading instead of a liquid sloshing model, for some combinations of curve, speed and grade the wheel unloading would be underestimated by 35 percentage points.

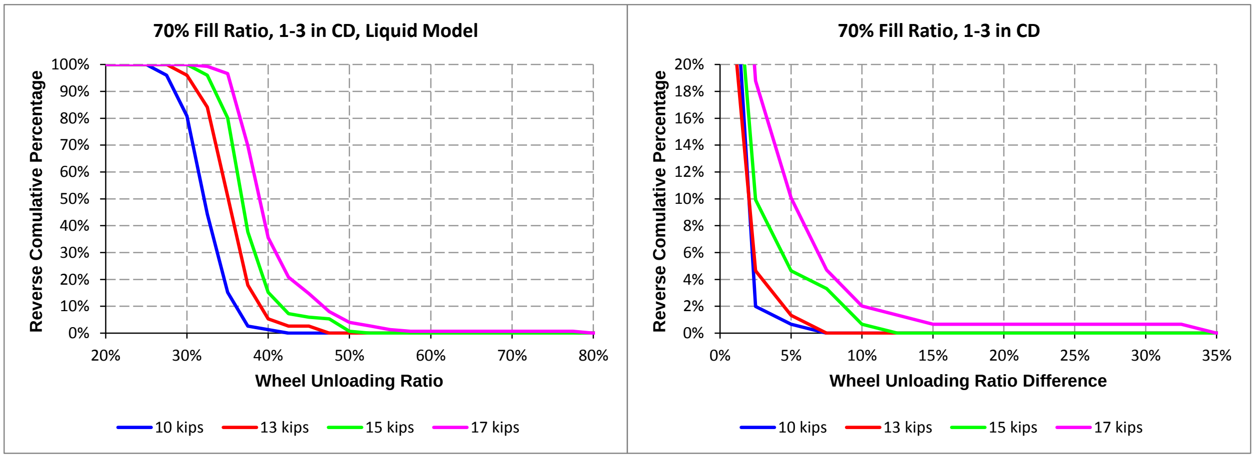

Figure 4-23: Reverse cumulative percentage for wheel unloading ratio and wheel unloading ratio difference at 70% fill ratio and various lateral in-train forces.

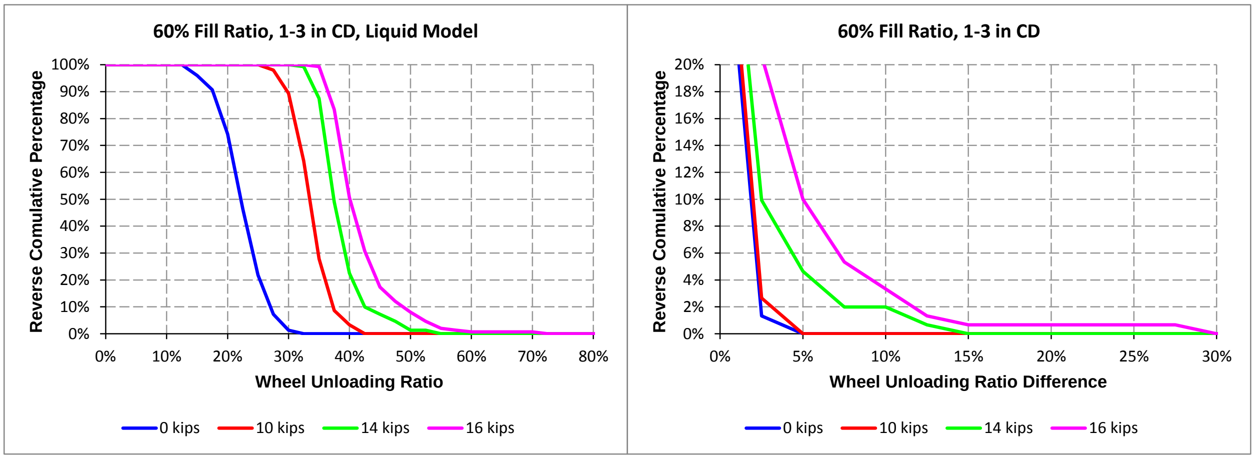

Figure 4-24: Reverse cumulative percentage for wheel unloading ratio and wheel unloading ratio difference at 60% fill ratio and various lateral in-train forces.

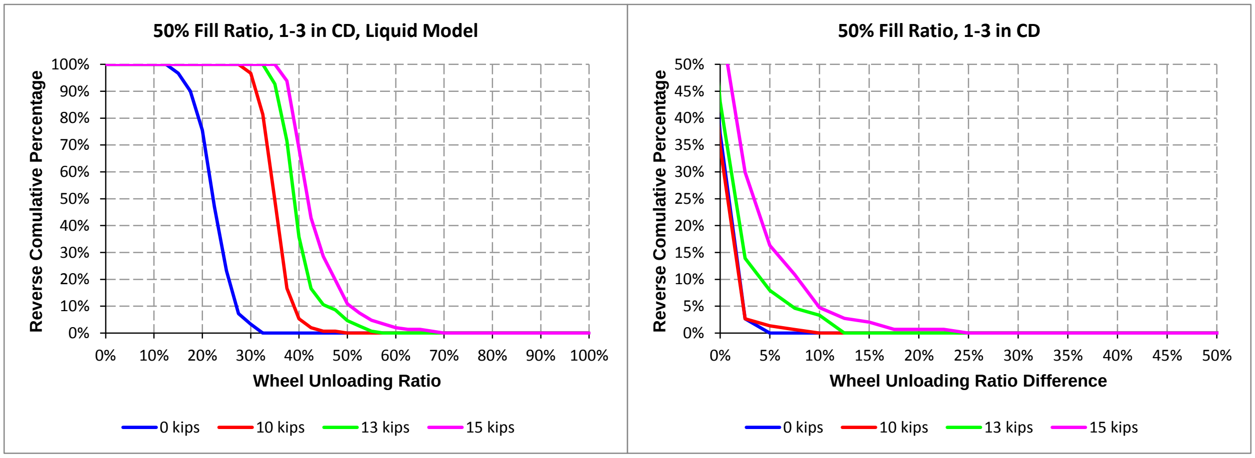

Figure 4-25 Reverse cumulative percentage for wheel unloading ratio and wheel unloading ratio difference at 50% fill ratio and various lateral in-train forces.

4.8 Effect of Fill Ratio

Reverse cumulative percentages for wheel unloading ratio and wheel unloading ratio difference with a 16 kip lateral in-train force and fill ratios of 50%, 60%, 70% and 80% are compared in Figure 4-26. The results show that, under the same lateral in-train force, the effect of tank car sloshing on wheel unloading decreases as fill ratio increases.

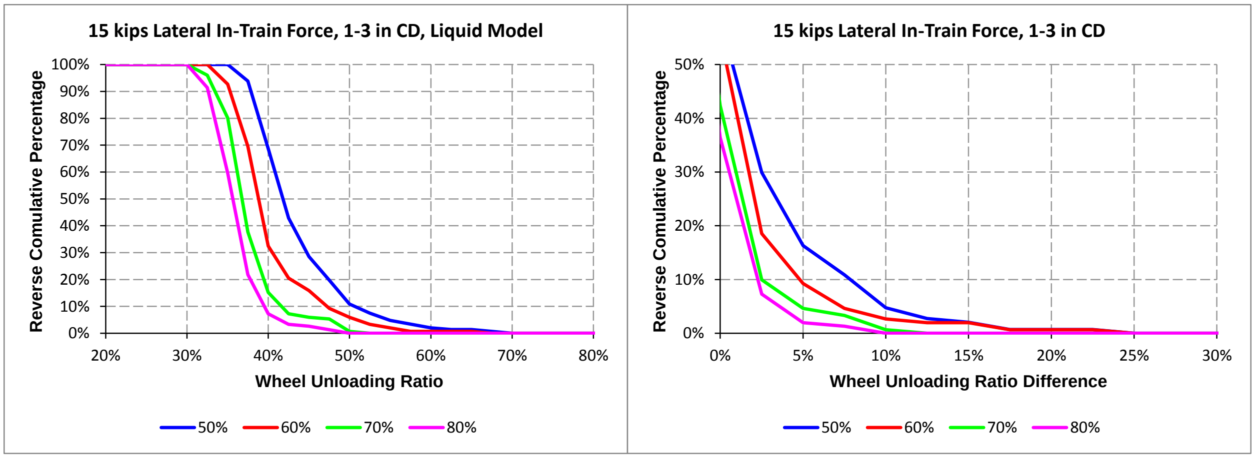

Figure 4-26 Reverse cumulative percentage for wheel unloading ratio and wheel unloading ratio difference at 15 kip lateral in-train force and various fill ratios.

Reverse cumulative percentages for wheel unloading ratio and wheel unloading ratio difference with 12 kip and 8 kip lateral in-train forces are shown in Figure 4-27 and Figure 4-28, respectively. Figure 4-26, Figure 4-27 and Figure 4-28 show that the effect of fill ratio on wheel unloading ratio difference decreases as lateral in-train force decreases. With an 8 kip lateral in-train force, wheel unloading ratio differences for all four fill ratios are close to one another and all are less than 5%.

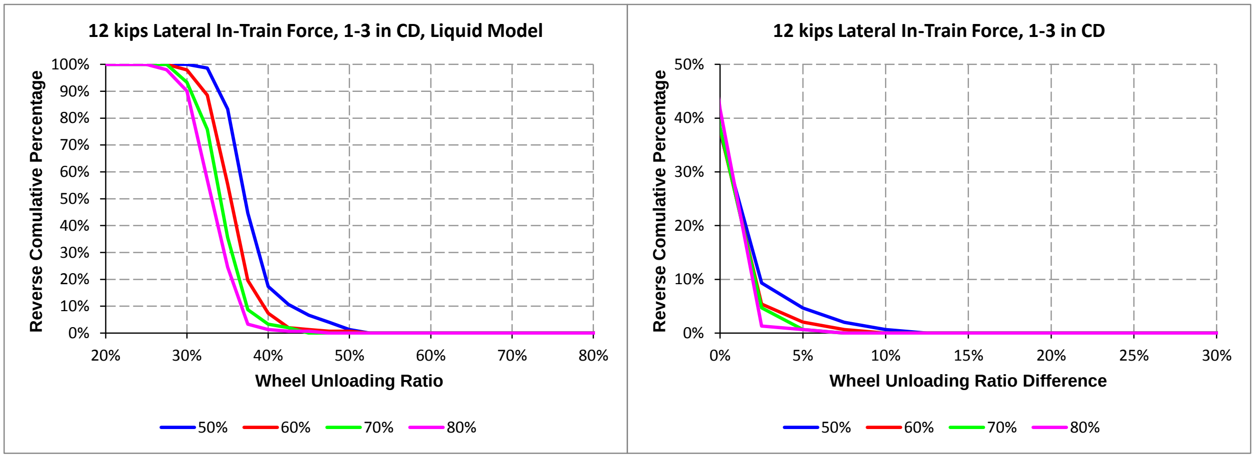

Figure 4-27: Reverse cumulative percentage for wheel unloading ratio and wheel unloading ratio difference with a 12 kip lateral in-train force and various fill ratios.

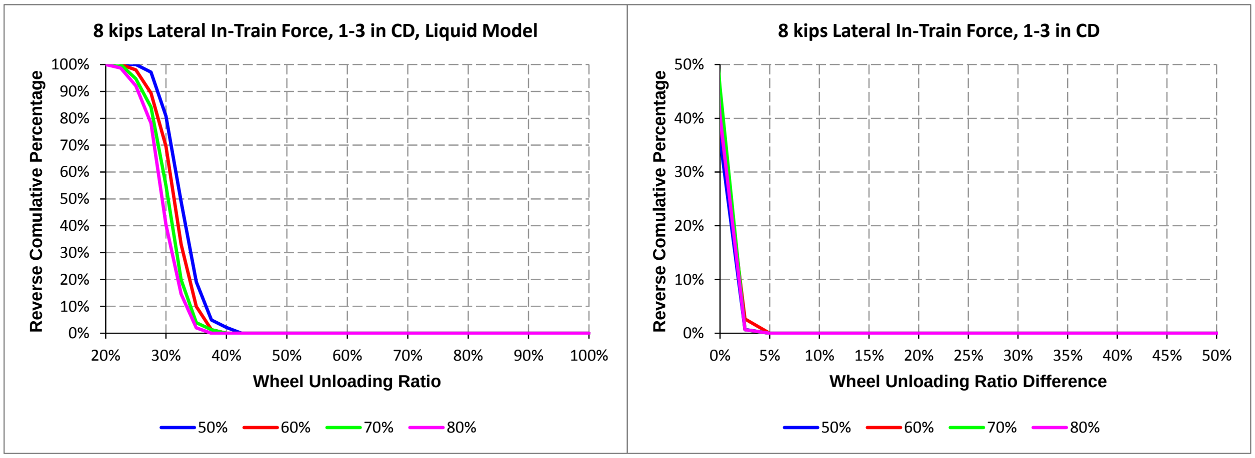

Figure 4-28: Reverse cumulative percentage for wheel unloading ratio and wheel unloading ratio difference with an 8 kip lateral in-train force and various fill ratios.

4.9 Case Study

In the field test, the tank car was connected to a lumber car with the specifications listed in Table 4-3.

Table 4-3: Lumber car information.

Car Number	SOO 601242	
Gross Rail Load	286,000	lb
Tare Weight	61,000	lb
Load Limit	225,000	lb
Car Length	80’7”	
Outside Extreme Width	9’10”	
Outside Extreme Height	15’6”	
Truck Center Length	60’4”	
Coupler Length	60”	

The curvature of the sharpest curve in the test track shown in Figure 4-1 is about 11.4°. The maximum buff force is assumed to be 200 kip. A buff in-train force is a longitudinal force that compresses the car along its length, thus forcing the car towards the outside of the track when it negotiates a curve. This can potentially result in a push-roll derailment where both trucks are pushed towards the outside of the track (and off the track) together, or in a jackknife derailment where only one of the trucks is pushed off the track and the two adjacent cars begin to fold in a manner similar to a jackknife closing. Two hundred kip is the highest allowable in-train buff force limit used by the North American freight industry [69] [70] [71], and it is the limit prescribed in the 2016 TC publication, “Marshalling Guidelines for Safe Operation of Freight Trains” [72].

Based on Equations (4-9) and (4-10), car length, truck center length and coupler length listed in Table 4-1 and Table 4-3, maximum curvature of 11.4° (503.42 feet curve radius) and maximum buff force of 200 kip, the maximum lateral in-train force F_y between the tank car and the lumber car is:

$$F_y = F \times \sin \emptyset = 200 \times$$

$$\sin\left\{180 - \operatorname{atan}\left(\frac{\sqrt{503.42^2 - \frac{37.83^2}{4}}}{\frac{52.83}{2} - 2.375}\right) - \operatorname{acos}\left[\frac{(2.375+5)^2 + \left(\frac{52.83}{2} - 2.375\right)^2 - \frac{37.83^2}{4} - \left(\frac{80.58}{2} - 5\right)^2 + \frac{60.33^2}{4}}{2(2.375+5)\sqrt{\left(\frac{52.83}{2} - 2.375\right)^2 + 503.42^2 - \frac{37.83^2}{4}}}\right]\right\}$$

≈8 kip

As shown in Figure 4-28, the maximum effect of tank car sloshing on wheel unloading is about 5% and the maximum wheel unloading ratio is about 43%.

If the tank car is connected to the same type of tank car, as in the case of a unit train, the maximum lateral in-train force F_y between the two tank cars can be calculated as follows:

$$F_y = F \times \sin \emptyset = = 200 \times$$

$$\sin\left\{180 - \operatorname{atan}\left(\frac{\sqrt{503.42^2 - \frac{37.83^2}{4}}}{\frac{52.83}{2} - 2.375}\right) - \operatorname{acos}\left[\frac{(2.375+5)^2}{2(2.375+5)\sqrt{\left(\frac{52.83}{2} - 2.375\right)^2 + 503.42^2 - \frac{37.83^2}{4}}}\right]\right\}$$

≈10 kip

Reverse cumulative percentages for wheel unloading ratio and wheel unloading ratio difference with a 10 kip lateral in-train force and fill ratios of 50%, 60%, 70% and 80% are shown in Figure 4-29. It can be seen the maximum effect of tank car sloshing on wheel unloading is about 10% and the maximum wheel unloading ratio is about 50%.

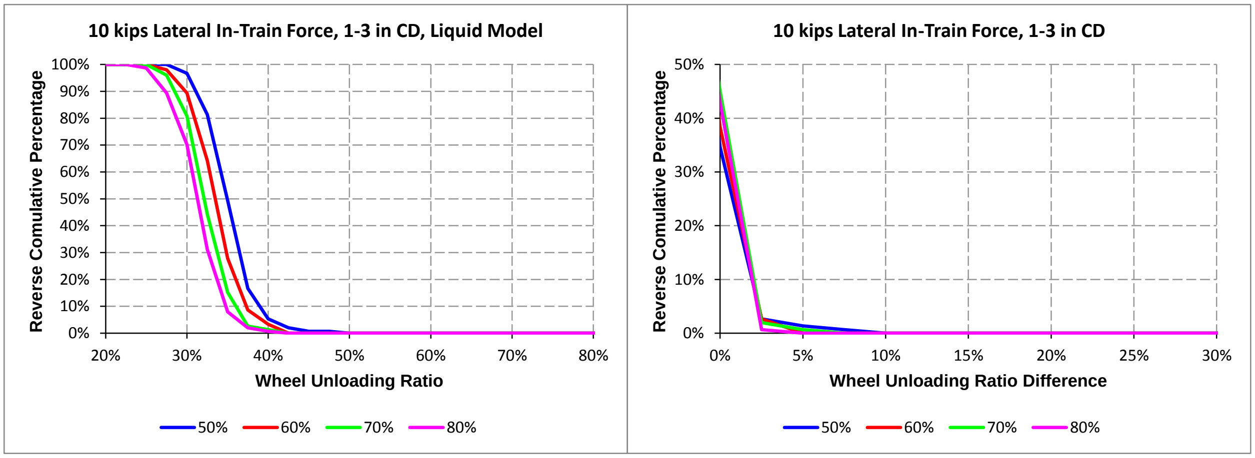

Figure 4-29: Reverse cumulative percentage for wheel unloading ratio and wheel unloading ratio difference with a 10 kip lateral in-train force and various fill ratios.

If the tank car is connected to a shorter car with a length of 37.75 ft, a truck center distance of 25.25 ft, and a coupler length of 28.5 in (2.375 ft) (a short car example from the AAR Train Make-Up Manual [71]), the lateral in-train force F_y between the two tank cars is:

$$F_y = F \times \sin\emptyset = \; = 200 \times$$

$$\sin\left\{180 - \mathrm{atan}\left(\frac{\sqrt{503.42^2 - \frac{37.83^2}{4}}}{\frac{52.83}{2} - 2.375}\right) - \mathrm{acos}\left[\frac{(2.375 + 2.375)^2 + \left(\frac{52.83}{2} - 2.375\right)^2 - \frac{37.83^2}{4} - \left(\frac{37.75}{2} - 2.375\right)^2 + \frac{25.25^2}{4}}{2(2.375 + 5)\sqrt{\left(\frac{52.83}{2} - 2.375\right)^2 + 503.42^2 - \frac{37.83^2}{4}}}\right]\right\}$$

≈15 kip

Reverse cumulative percentages for wheel unloading ratio and wheel unloading ratio difference with a 10 kip lateral in-train force and fill ratios of 50%, 60%, 70% and 80% are shown in Figure 4-30. It can be seen the maximum wheel unloading ratio is about 70%.

Figure 4-30 shows that the largest wheel unloading ratio difference is about 25%, and it occurs in the case where there was a 50% fill ratio, 1 to 3 inches of cant deficiency, and a 15 kip lateral in-train force. Thus, if a solid model were used to estimate the wheel unloading instead of a liquid sloshing model, for some combinations of curve, speed and grade the wheel unloading would be underestimated by 25 percentage points.

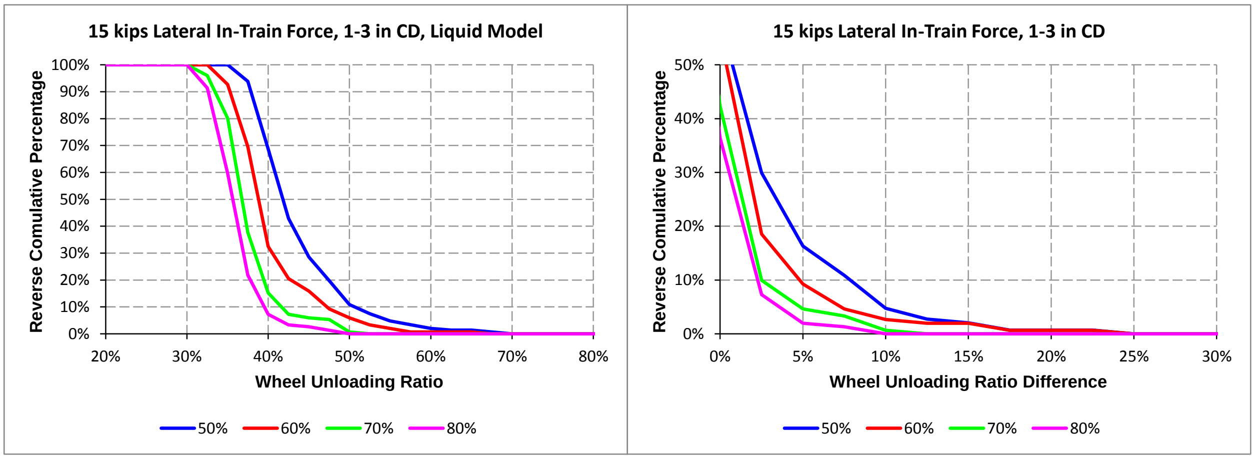

Figure 4-30: Reverse cumulative percentage for wheel unloading ratio and wheel unloading ratio difference with a 15 kip lateral in-train force and various fill ratios.

4.10 Tank car sloshing effect flowchart

The maximum buff of 200 kip is used in the case study in the previous section. The actual buff force is dependent upon train operation, grade and position of the tank car in a train.

Lateral in-train force under draft and buff conditions can be calculated as follows [69] [71]:

$$F_{\mathrm{y\_draft}} = TT \times (20 \times \%Grade + 4.5 + 0.4 \times Curve + 1.52 \times A) \times sin(\emptyset) \qquad (4\text{-}11)$$

$$F_{\mathrm{y\_buff}} = TT \times (20 \times \%Grade - 4.5 - 0.4 \times Curve - 1.52 \times A) \times sin(\emptyset) \qquad (4\text{-}12)$$

where:

Fy_draft = Lateral in-train force under draft condition (lb)
Fy_buff = Lateral in-train force under buff condition (lb)
TT = Trailing Tonnage (ton)

20 = Grade resistance constant (lb/ton/%Grade)
%Grade = Grade in percentage
4.5 = Rolling resistance constant (lb/ton)
0.4 = Curve resistance constant (lb/ton/deg)
Curve = Degree of curvature (°)
1.52 = Conversion constant (lb min/ton/mph)
A = Acceleration (mph/min), zero if speed is constant

Trailing tonnage is the total net weight (in tons) of all cars following the car in question, back to the next locomotive (in the case of distributed power train) or back to the end of train (in the case of non-distributed power train).

Higher grade and higher trailing tonnage result in higher in-train force. To reduce the trailing tonnage of a tank car with low fill ratio, it is recommended that the tank car be placed as far behind a locomotive as possible.

As shown in Equation (4-10), coupler angle is a function of curvature and car length, truck center distance and coupler length of two adjoining cars. In general, the longer the car in question is in comparison with the car at the other end of the coupler, the higher the coupler angle is.

The following conclusions can be made from the dynamic simulations:

- the main conditions that increase the effect of tank car sloshing on wheel unloading (and hence safety) are reductions in fill ratio, increases in cant deficiency, and increases in lateral in-train force;
- increases in cant deficiency are caused by increases in train speed, increases in curvature, and reductions in superelevation;
- increases in lateral in-train force are caused by increases in coupler force, and increases in coupler angle;
- increases in coupler force are caused by increases in grade, and increases in trailing tonnage; and
- increases in coupler angle are caused by increases in track curvature and increases in car length, the truck centre distance and coupler length differences between two adjoining cars.

These effects are shown graphically in the tank car sloshing flowchart in Figure 4-31.

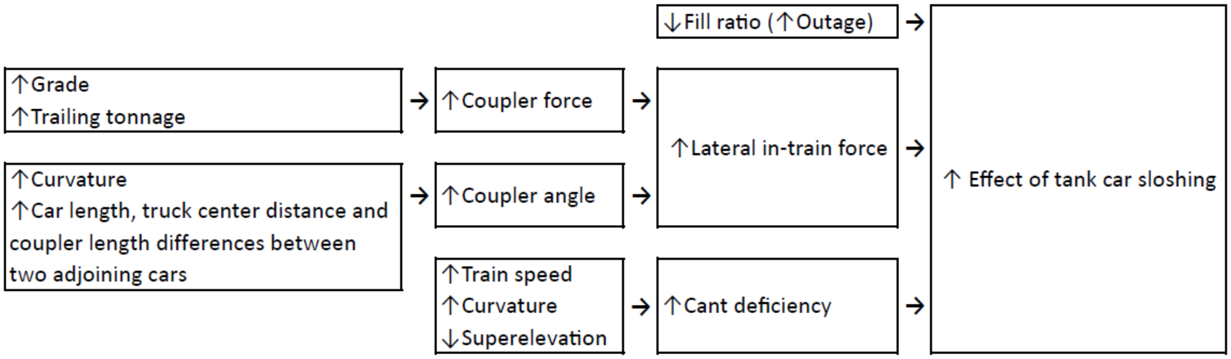

Figure 4-31: Tank car sloshing effect flowchart (from dynamic simulations).

It is recommended that physical tests of tank car sloshing be conducted to validate and improve simulation models.

It is also recommended that a tool be developed to calculate the derailment risk based on the developed tank car simulation models and the tank car sloshing effect flowchart shown in Figure 4-31. The tool can be used by regulators to develop guidelines on tank car sloshing and by railroads to improve train marshaling practice.

5 SUMMARY AND RECOMMENDATIONS

5.1 Literature review

A tank sloshing literature review of over 70 references was performed. A broad range of applications was covered by the literature including rail transport, road vehicles, aerospace, marine transport, etc. However, a focus was placed on physical tests and computer simulations related to rail transport. The literature suggests that several rail operating conditions may be negatively affected by sloshing:

- potential for more derailments (e.g. [13], [14], [15], [16], [18], [60]);
- increased magnitudes and oscillations of longitudinal forces during braking (e.g. [10], [11]);
- increased overturning risks (e.g. [14], [15], [16]);
- increased hunting instability at high speeds (e.g. [18]).

It is recommended that further research be conducted that includes both physical testing and computer simulations to better understand these tank car sloshing risks.

No reports were found of stochastic studies to investigate the safety performance of railway tank cars operating in a wide range of load and operating conditions. The current report demonstrates that this methodology has strong potential to provide a comprehensive assessment of how known variations in a wide range of environmental factors (e.g., train speed, car position in a train, track geometry, etc.) can be used to assess the extent to which various combinations of factors could combine with tank sloshing to produce significant reductions in tank car safety.

5.2 Review of TSB Accident and Incident Data and a Survey of Industry Experts

The TSB was not aware of any recent TSB investigations where liquid sloshing was determined to be the cause of a derailment. The TSB database of published accident reports was searched no derailment reports were found that attributed sloshing as a cause. A search of the TSB RODS database identified a report were sloshing was described in relation to a yard derailment but it is not known if sloshing played a role in this yard derailment or it was simply observed to occur due to the derailment or other car movements.

In one RODS item (RODS R06V0272) a worker was injured when a "***sloshing*** *action from the tank moved the car forward".* This is the only instance of sloshing being attributed to a safety related incident. This took place in a yard, not on mainline track, and did not involve a derailment. The potential for sloshing to cause a car to move unexpectedly in yard or switching operations was later confirmed by discussions with experienced industry experts. None of the experts interviewed knew of an instance where an underfilled tank car had caused a safety issue or a concern, and in general sloshing of liquids within a tank car during transit on mainline track was not seen as a safety concern.

To summarize:

- Sloshing of liquids within a rail tank car has never been attributed as the cause of a derailment or a mainline accident. (This does not mean that sloshing has not ever been the cause of a derailment, only that it has not to date been attributed as being the cause of a derailment.)

- Sloshing does occur during yard and switching operations, where the sloshing forces may cause a car to move unexpectedly. There is one reported injury related to this type of sloshing action during a yard operation.
- Sloshing forces do cause train action motions that locomotive engineers have noted.
- Tank cars can be partially filled as part of regular shipping operations and may occur as single cars or as several cars in a unit train consist.

5.3 Dynamic Simulations

Analytical work was conducted to assess the extent to which movement of liquid in a tank car could contribute to derailments of trains carrying liquid dangerous goods.

A new pendulum equivalent mass model (EMM) was developed to simulate the effect of liquid sloshing in railway tank cars with formulas generated based on Finite Element Analysis data. This liquid sloshing model was then incorporated into the empty tank car MBD model that NRC developed and validated in a 2009-2012 study on the impact of curvature on track geometry safety standards. The ability of the empty tank car model to predict wheel forces accurately in curves was validated using wheel force data obtained from Instrumented Wheelset (IWS) transducers installed on an empty tank car and operated over more than 523 miles of CN and CP track with 1,340 curves between Vancouver and Kamloops, BC. While the majority of the curves were between 2° and 8°, 18 very sharp curves of more than 10° were included. The sharpest curvature was about 11.4°.

The new pendulum model of liquid slosh, the empty tank car model from 2009-12, and the track geometry data from the 2009-12 were combined together to allow the simulation of a tank car with a sloshing payloads of various sizes, as it operates over more than 1,000 of the curves from the 2009-12 study.

For comparison purposes, a solid-payload tank car model was also developed by taking the validated empty tank car model and adding a non-moving payload located in the bottom of the tank.

Hundreds of thousands of dynamic simulations were conducted for the tank car with liquid cargo at various fill ratios and with equivalent solid (i.e., rigid) cargo on more than 1,000 measured curves. The liquid was assumed to have a density of 1,000 kg/m^3, the upper limit of the range of densities given by API for heavy crude oil (920 -1,000 kg/m^3).
The simulation results show that tank car sloshing has a much higher impact on wheel unloading than on wheel climbing. Therefore, the wheel unloading ratio (see Footnote 3 on page 11) was used in this study as a safety measure to analyze the impact of tank car sloshing on rail transportation safety.

The largest difference in wheel unloading ratio predicted by the liquid model relative to that predicted by the solid model was about 35%, and it occurred in the case where there was a 70% fill ratio, 2 to 3 inches of cant deficiency, and a 17 kip lateral in-train force. Thus, if a solid model were used to estimate the wheel unloading instead of a liquid sloshing model, for some combinations of curve, speed and grade the wheel unloading would be underestimated by 35 percentage points (i.e., the wheel unloading ratio would be estimated to be 45% instead of

80%). ***It is strongly recommended that future investigations of tank car safety behaviour in this operating regime make use of effective dynamic sloshing models.***

The simulation results show that, on the measured curves, when there is no in-train force, the maximum effect of tank car sloshing on wheel unloading is about 5% at cant deficiencies up to 3 inches and 8% at cant deficiencies up to 4 inches. The effect of tank car sloshing on wheel unloading increases with cant deficiency. At cant deficiencies less than 1 inch, the effect of tank car sloshing is small.

The EMM model of tank car sloshing used for this study was based on a Finite Element Analysis simulation model of liquid sloshing in a tank, without having any physical measurements of actual fluid motions. ***It is recommended that physical tests of tank car sloshing be conducted to validate and improve the simulation models.***

The effect of tank car sloshing on derailment risk increases with the increase of lateral in-train force or the decrease of fill ratio. ***Therefore, it is recommended that special attention be paid to tank cars with low fill levels and high lateral in-train forces.*** For example, a lateral in-train force of 15 kip could occur if the tank car was connected to a much shorter car and then placed at the front of the train. In this circumstance, tank car sloshing could increase wheel unloading by 35% at a fill ratio of 50%.

Lateral in-train force is equal to coupler force multiplied by the sine of coupler angle. In general, high grade and high trailing tonnage lead to high coupler force, and high car length difference between the car in question and a shorter adjoining car leads to higher coupler angle.

It is recommended that a tank car with low fill ratio be connected to cars with the same or longer car length. If a tank car with low fill ratio has to be connected to a much shorter car, it is recommended that the car be placed as far behind a locomotive as possible. As shown in the flowchart in Figure 4-31, there are many conditions that can increase the effect of tank car sloshing on derailment risk. They should all be considered to accurately evaluate the derailment risk of a partially filled tank car.

The simulation results show that the effect of tank car sloshing on wheel unloading, and hence on tank car safety, is increased when there are significant reductions in fill level, high levels of cant deficiency, and high levels of lateral in-train force. However, this report does not take into account the probability of these individual events occurring, or the likelihood that a given combination would occur simultaneously. **It is recommended that further investigations be conducted to identify or estimate probability distributions for reductions in fill ratio, high levels of cant deficiency and high levels of lateral in-train force, and use them to estimate the probability of tank car sloshing leading to wheel unloading that could potentially cause a derailment.**

The simulation results in this report do not take into account the consequences (e.g., the cost) of an accident where tank car sloshing was a significant factor. **It is recommended that the consequences (e.g., costs) of the derailment be taken into account in future investigations into the risk of tank car sloshing and the possibility that it could cause a derailment.**

It is recommended that further investigation be conducted to improve the liquid-slosh model and develop tool that regulators and railroads can use to develop improved

guidelines on train marshalling practices. This would include, for example, various states of wear for wheels, friction wedges and other car components and systems.

An international workshop on the effects of tank car sloshing on rail transportation safety was held in Ottawa on 25 August 2017, with participants from academia, industry, government and R&D centres in Canada, USA, Russia, Australia and China. Findings on the effect of tank car sloshing from NRC and other research organizations have been presented***. A substantial amount of positive feedback from participants was received regarding the establishment of an international collaborative initiative on railway tank car sloshing.***

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Appendix A Wheel Unloading Simulation Results

A.1 80% Fill Ratio (14% Outage)

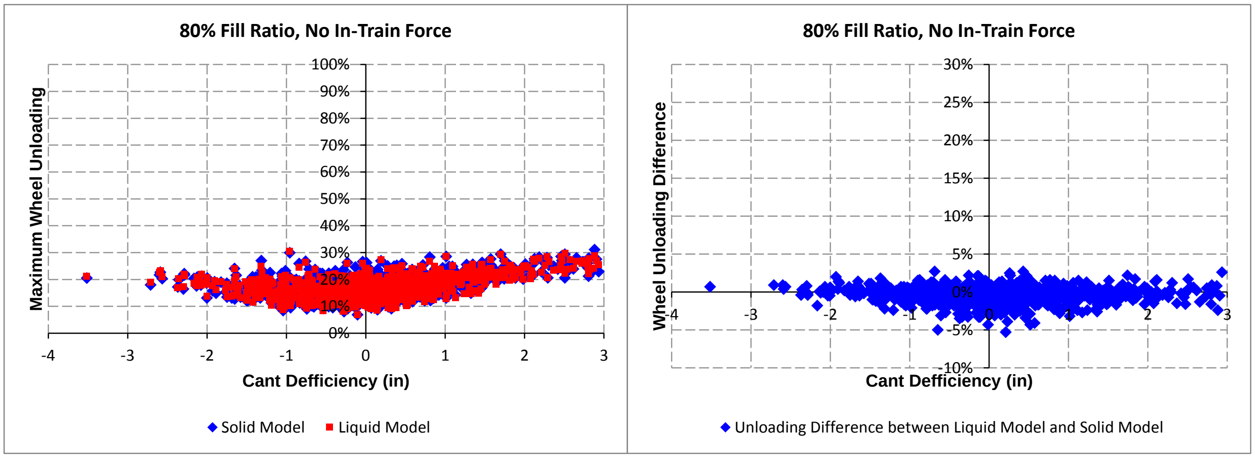


Figure A.1 Wheel unloading versus cant deficiency at 80% fill ratio and no in-train force

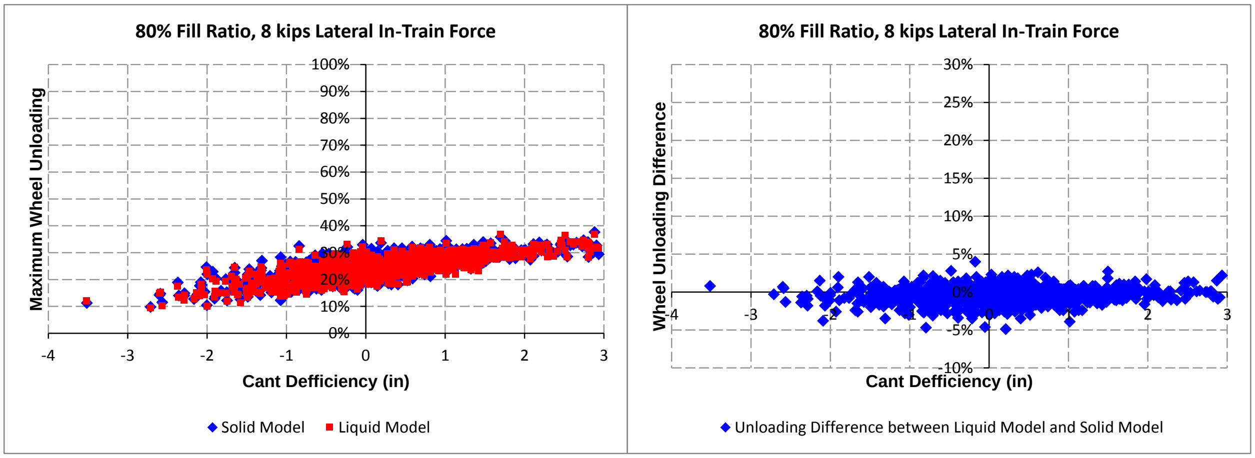


Figure A. 2 Wheel unloading versus cant deficiency at 80% fill ratio and 8 kip lateral in-train force

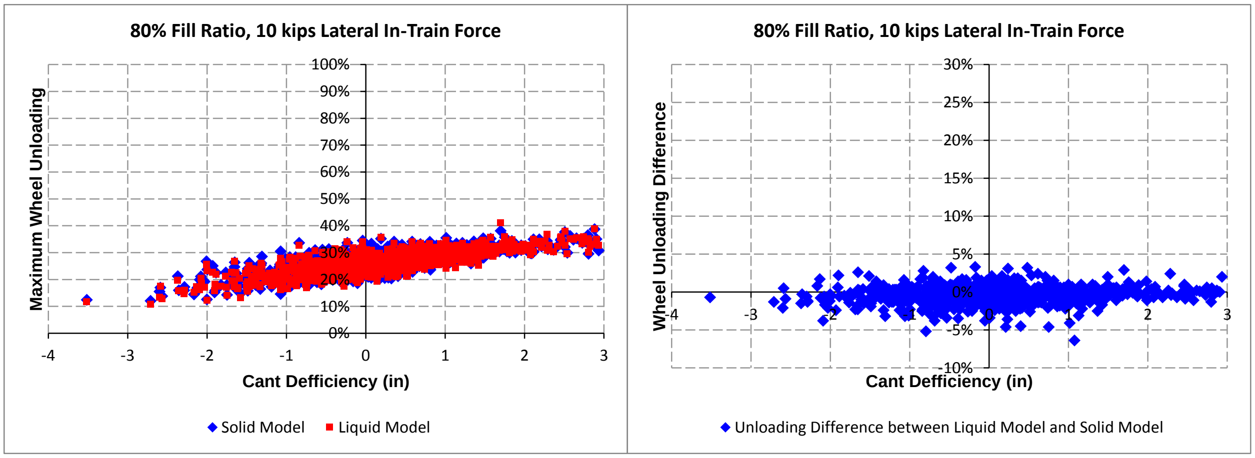


Figure A. 3 Wheel unloading versus cant deficiency at 80% fill ratio and 10 kip lateral in-train force

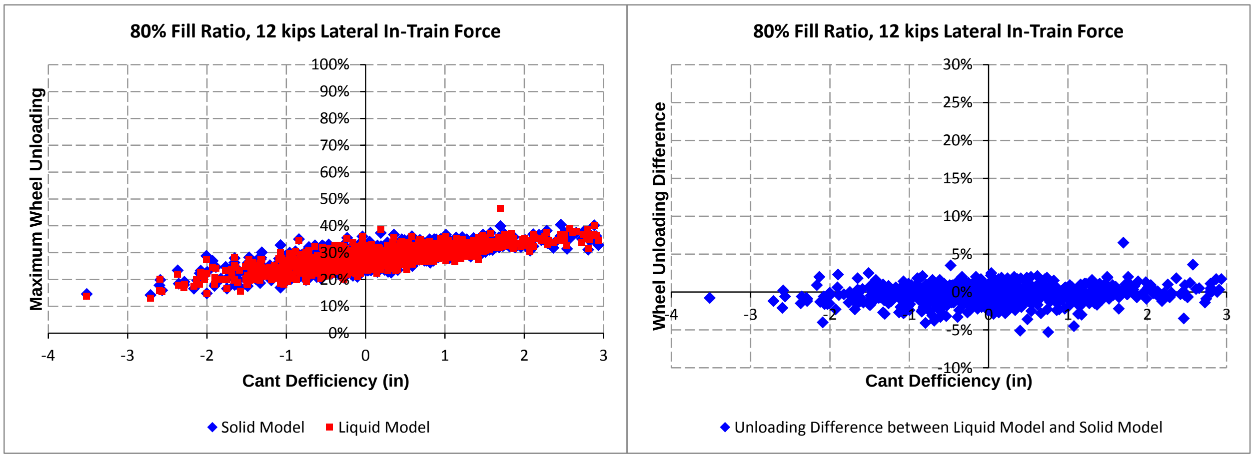


Figure A. 4 Wheel unloading versus cant deficiency at 80% fill ratio and 12 kip lateral in-train force

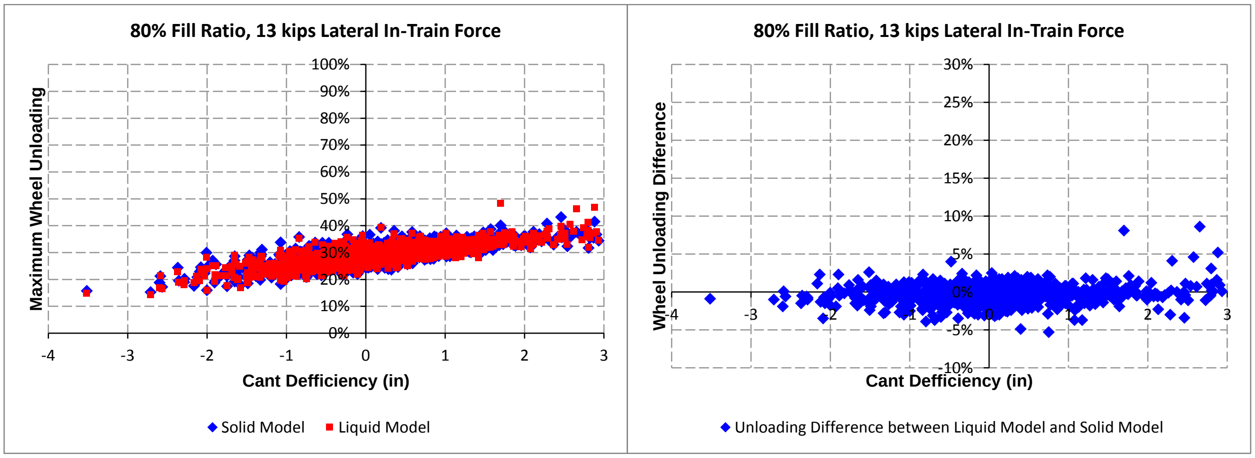


Figure A. 5 Wheel unloading versus cant deficiency at 80% fill ratio and 13 kip lateral in-train force

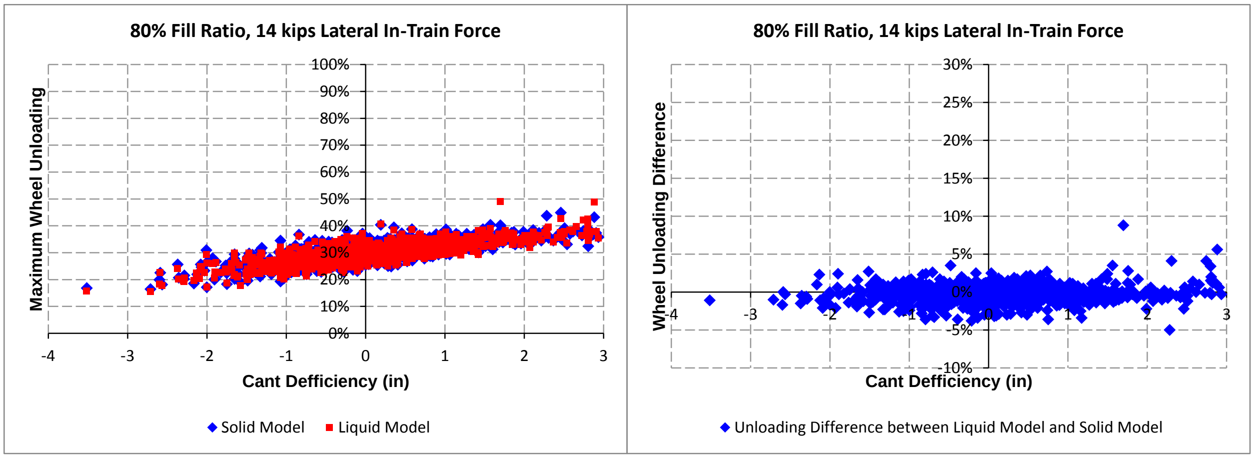


Figure A. 6 Wheel unloading versus cant deficiency at 80% fill ratio and 14 kip lateral in-train force

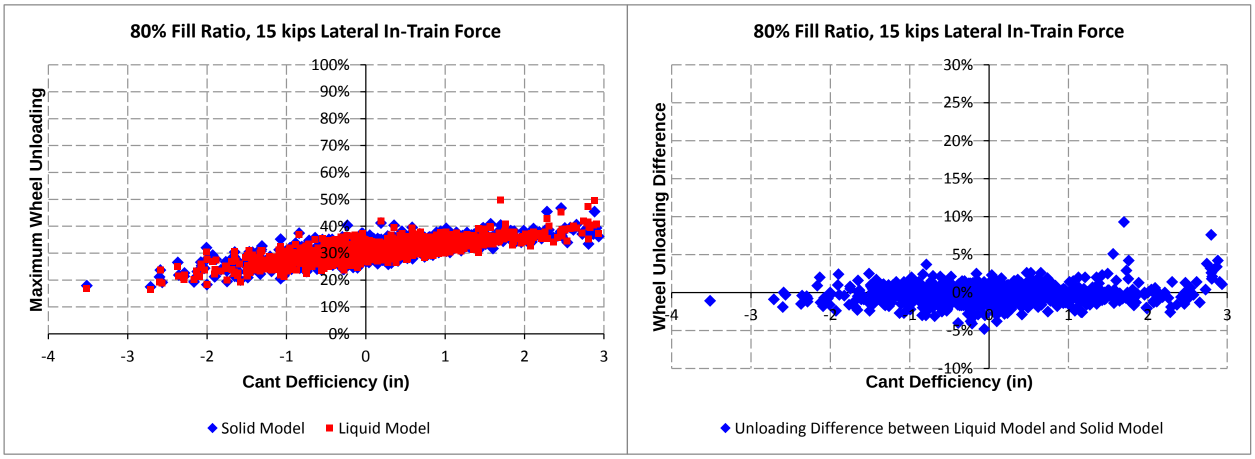


Figure A. 7 Wheel unloading versus cant deficiency at 80% fill ratio and 15 kip lateral in-train force

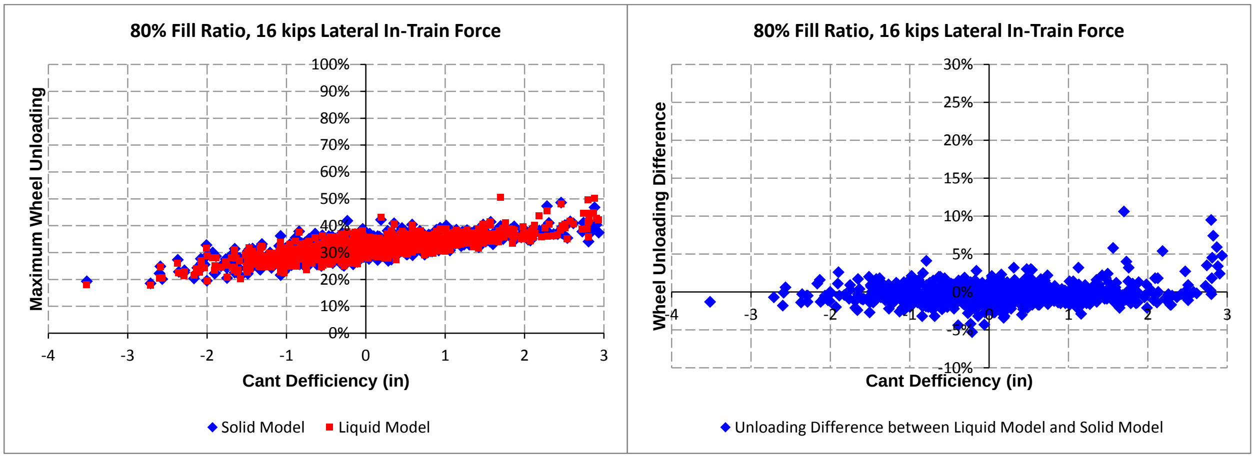


Figure A. 8 Wheel unloading versus cant deficiency at 80% fill ratio and 16 kip lateral in-train force

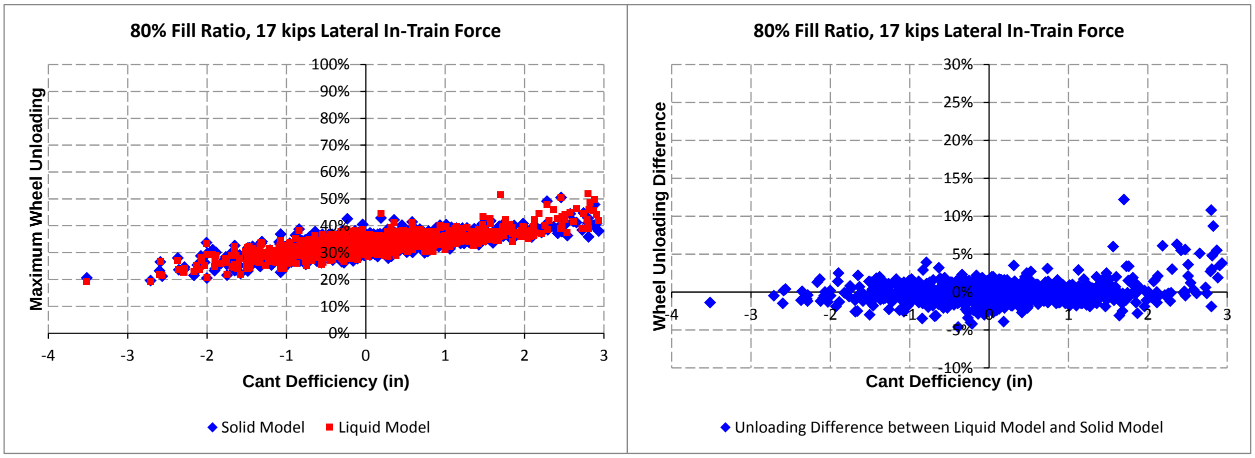


Figure A. 9 Wheel unloading versus cant deficiency at 80% fill ratio and 17 kip lateral in-train force

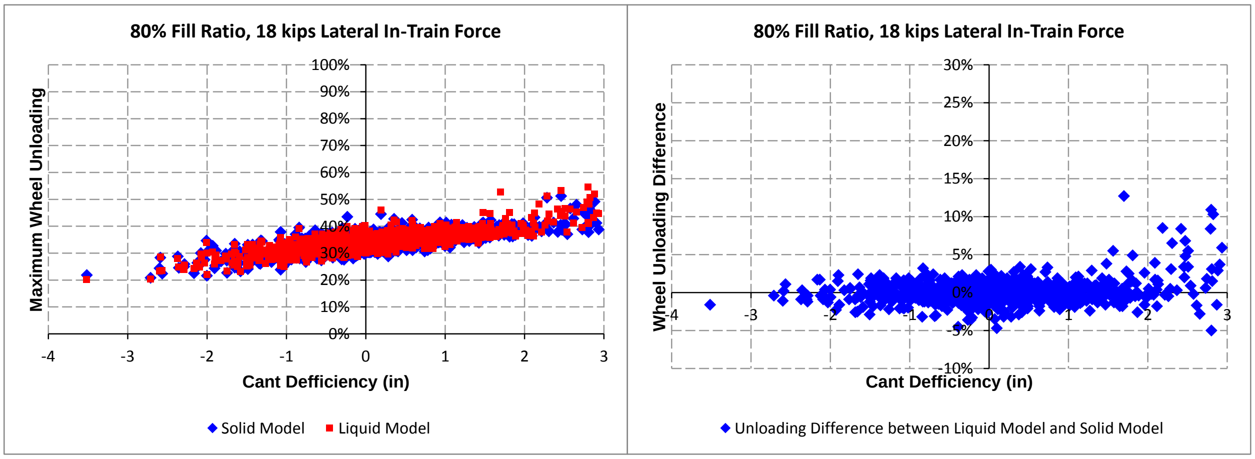


Figure A. 10 Wheel unloading versus cant deficiency at 80% fill ratio and 18 kip lateral in-train force

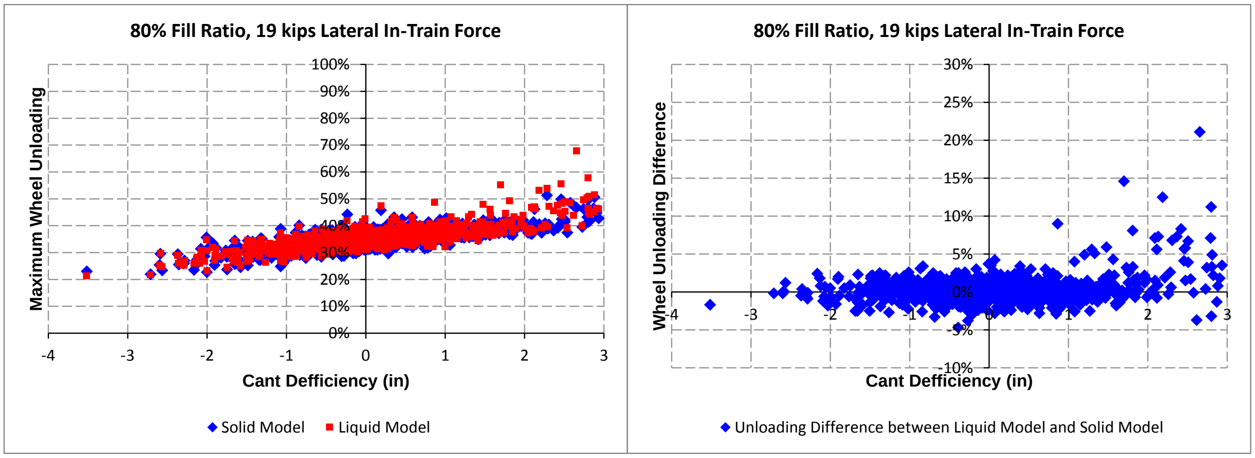


Figure A. 11 Wheel unloading versus cant deficiency at 80% fill ratio and 19 kip lateral in-train force

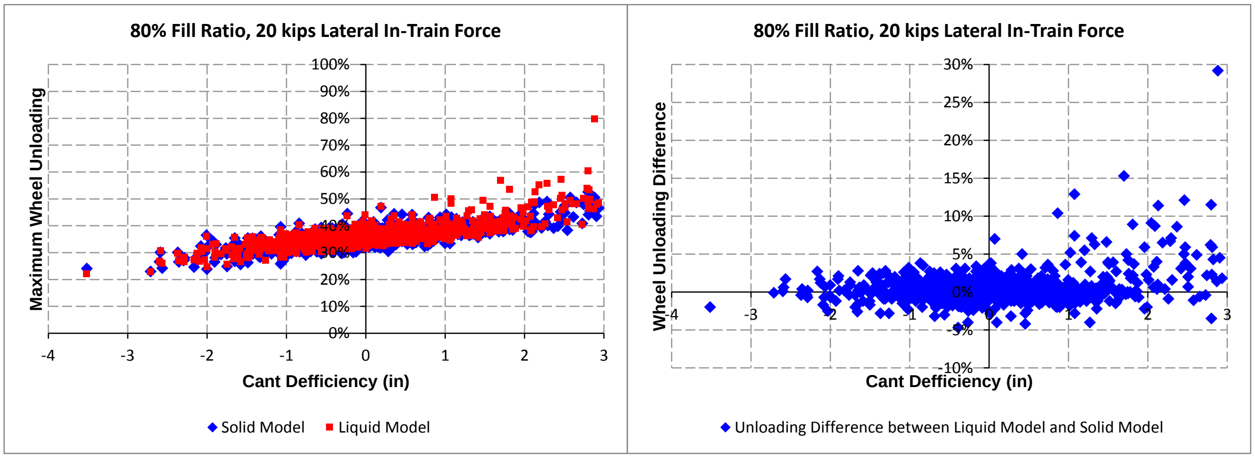


Figure A. 12 Wheel unloading versus cant deficiency at 80% fill ratio and 20 kip lateral in-train force

A.2 Simulation Results at 70% Fill Ratio (25% Outage)

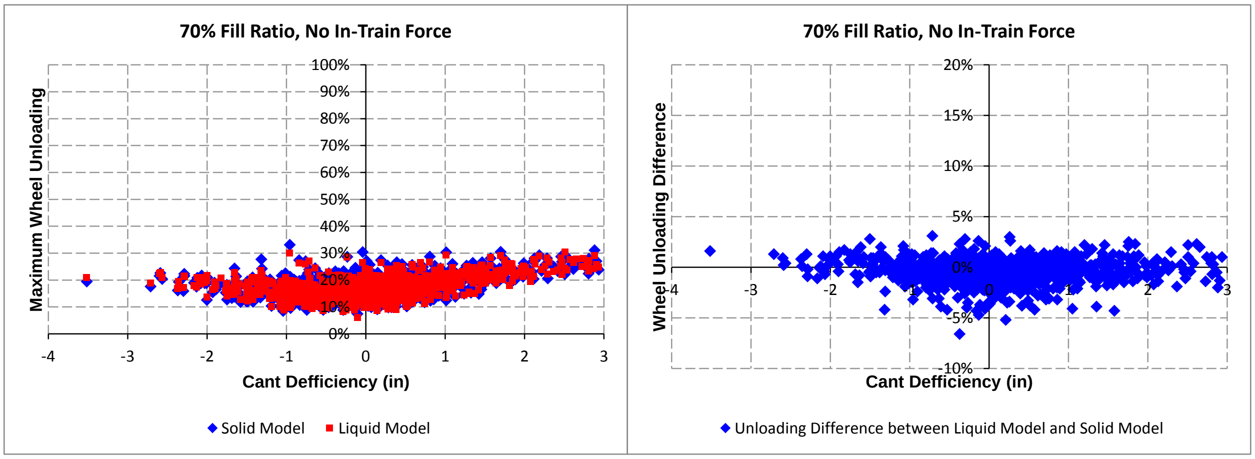


Figure A. 13 Wheel unloading versus cant deficiency at 70% fill ratio and no in-train force

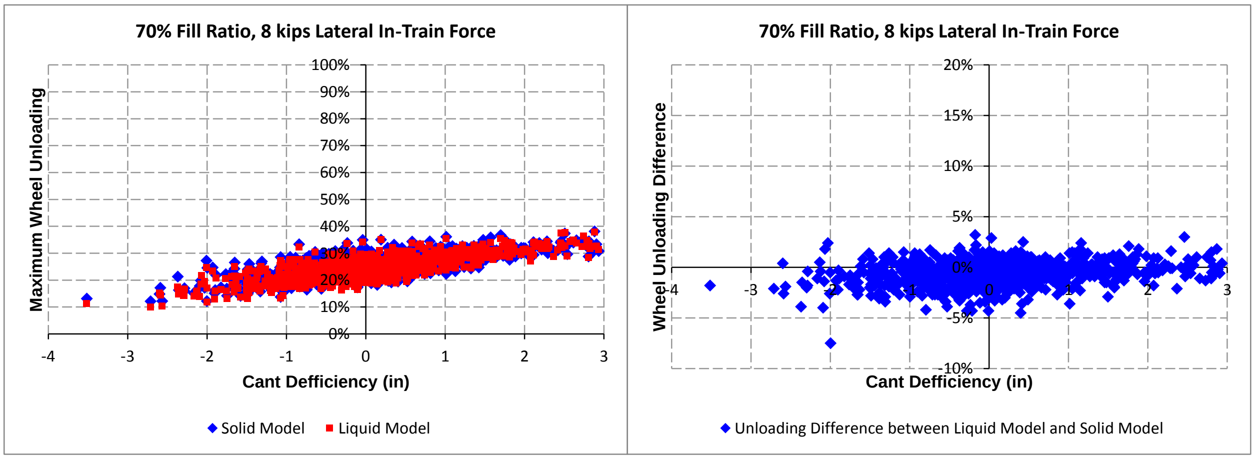
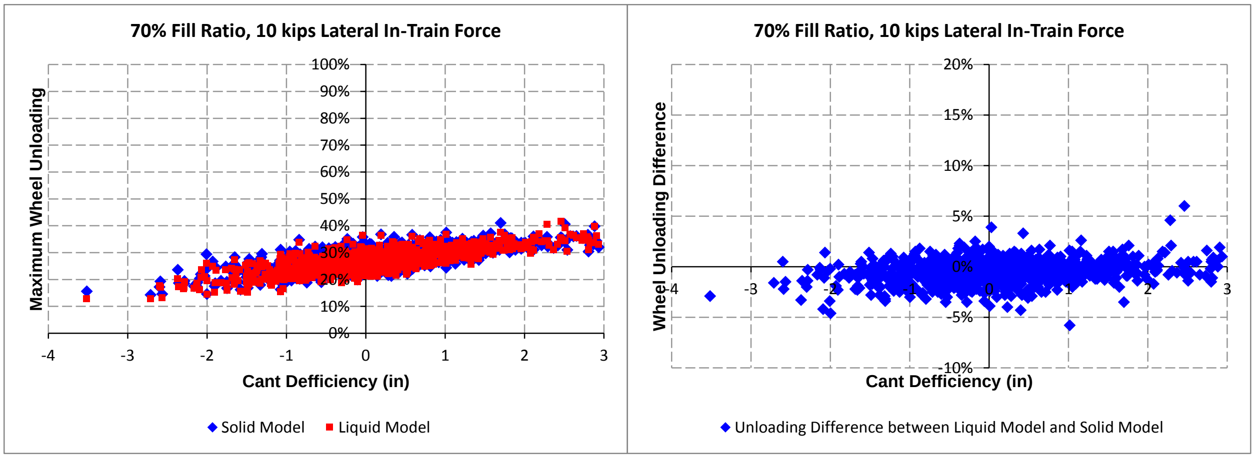
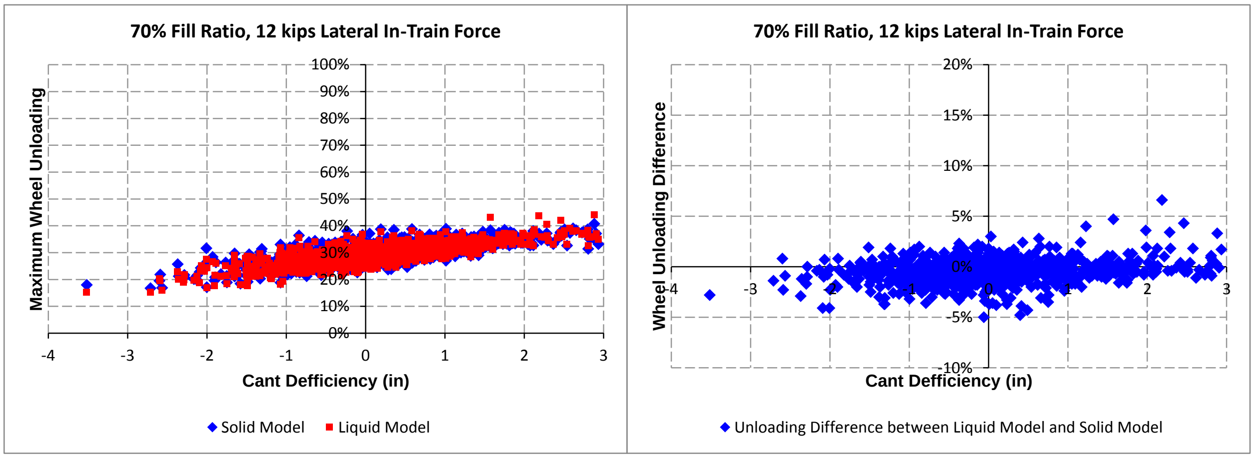


Figure A. 14 Wheel unloading versus cant deficiency at 70% fill ratio and 8 kip lateral in-train force


70% Fill Ratio, 10 kips Lateral In-Train Force

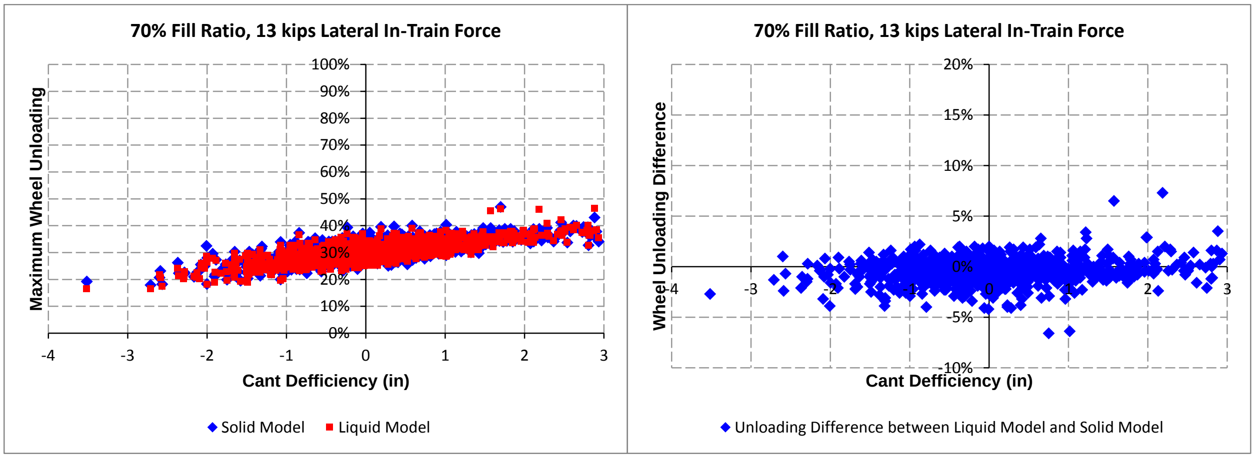
70% Fill Ratio, 10 kips Lateral In-Train Force

Figure A. 15 Wheel unloading versus cant deficiency at 70% fill ratio and 10 kip lateral in-train force


70% Fill Ratio, 12 kips Lateral In-Train Force

70% Fill Ratio, 12 kips Lateral In-Train Force

Figure A. 16 Wheel unloading versus cant deficiency at 70% fill ratio and 12 kip lateral in-train force


70% Fill Ratio, 13 kips Lateral In-Train Force

70% Fill Ratio, 13 kips Lateral In-Train Force

Figure A. 17 Wheel unloading versus cant deficiency at 70% fill ratio and 13 kip lateral in-train force

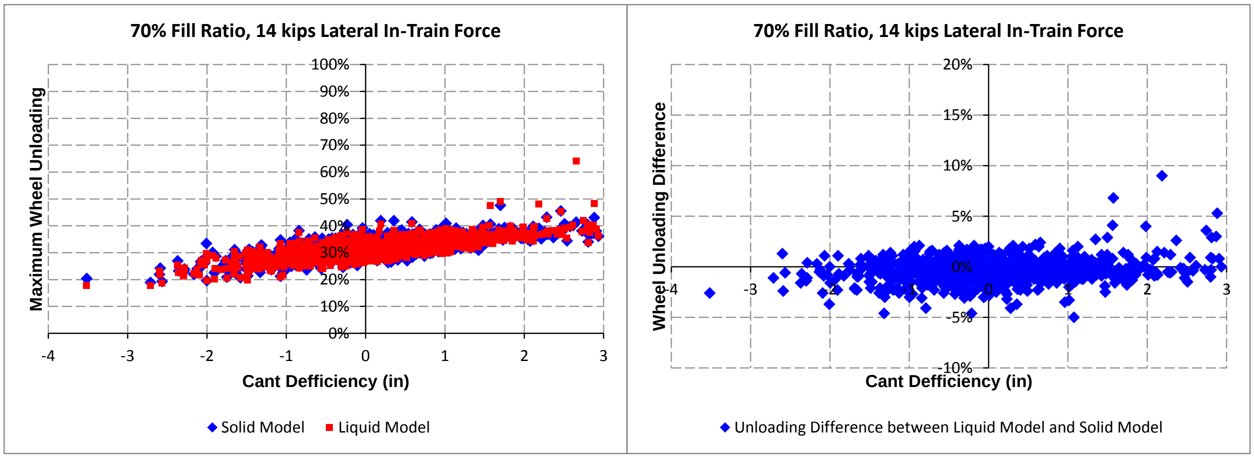


Figure A. 18 Wheel unloading versus cant deficiency at 70% fill ratio and 14 kip lateral in-train force

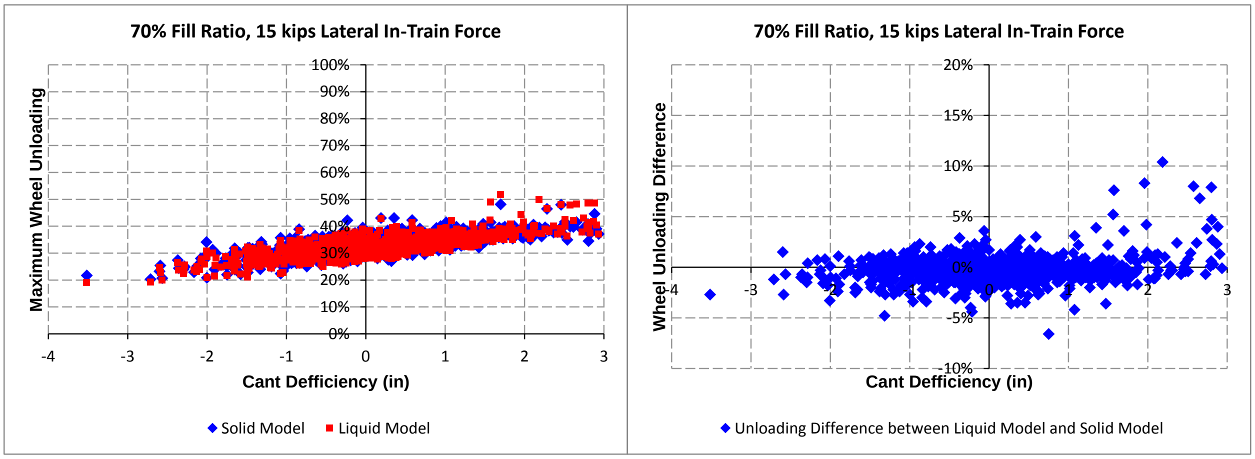


Figure A. 19 Wheel unloading versus cant deficiency at 70% fill ratio and 15 kip lateral in-train force

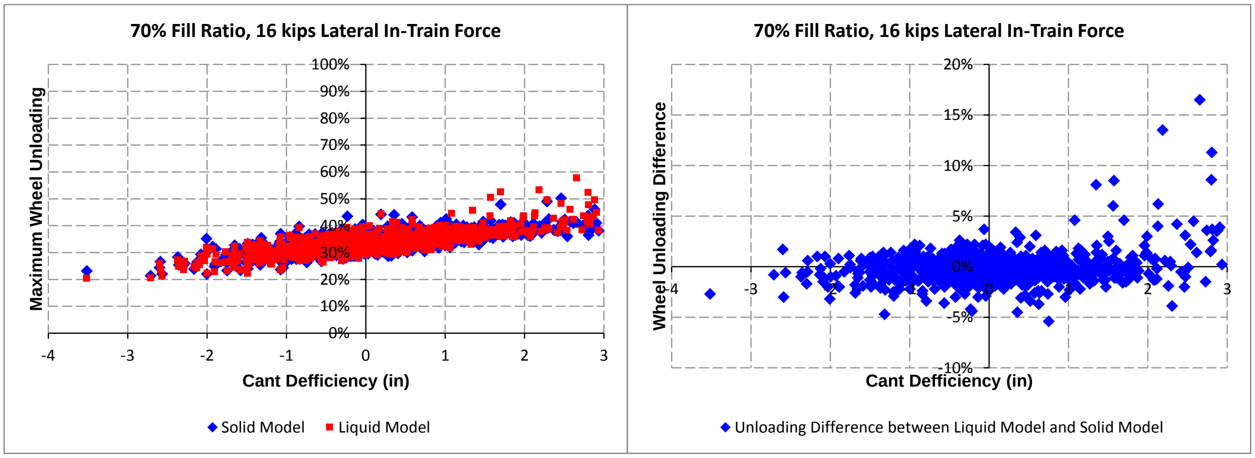


Figure A. 20 Wheel unloading versus cant deficiency at 70% fill ratio and 16 kip lateral in-train force

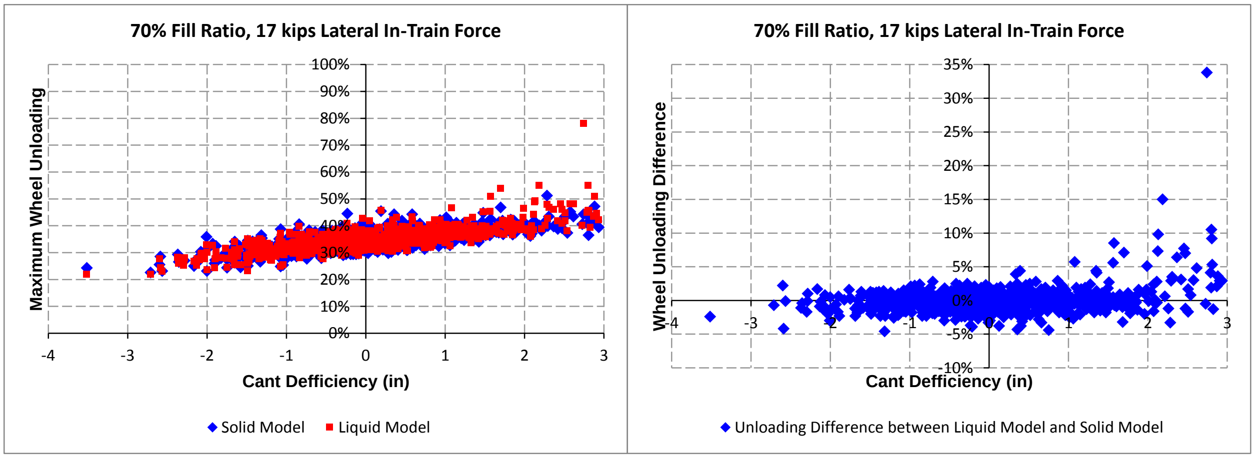


Figure A. 21 Wheel unloading versus cant deficiency at 70% fill ratio and 17 kip lateral in-train force

A.3 Simulation Results at 60% Fill Ratio (37% Outage)

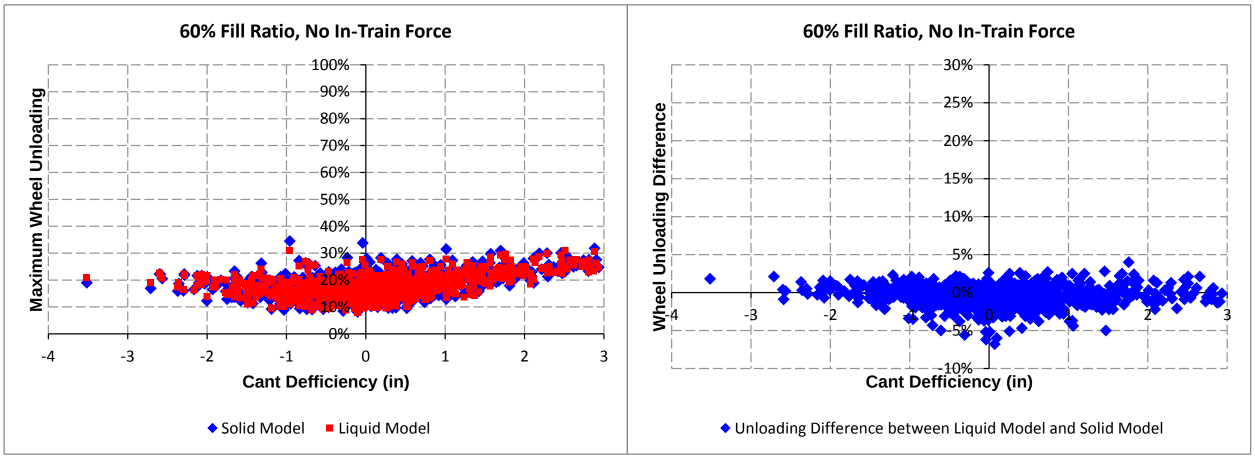


Figure A. 22 Wheel unloading versus cant deficiency at 60% fill ratio and no in-train force

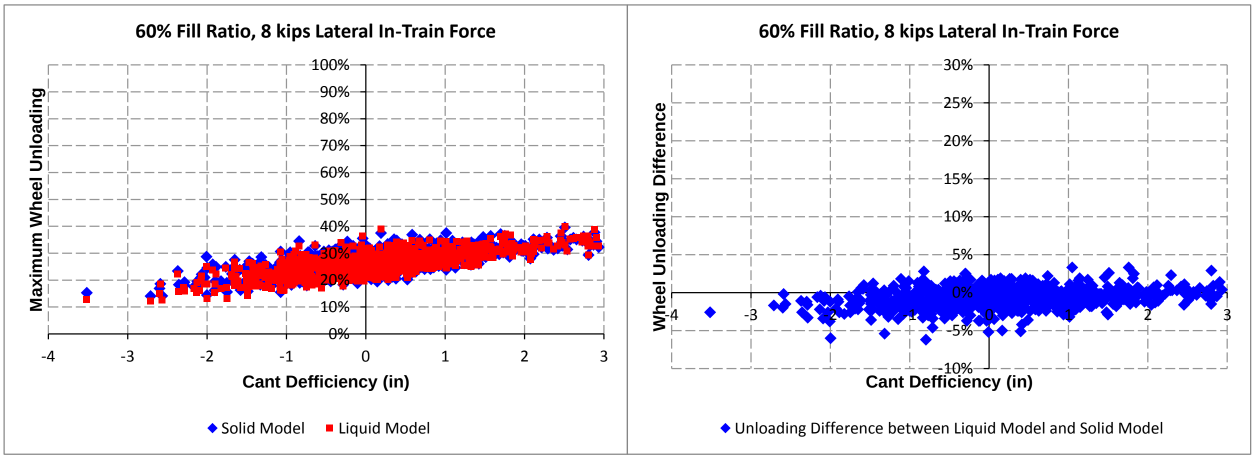


Figure A. 23 Wheel unloading versus cant deficiency at 60% fill ratio and 8 kip lateral in-train force

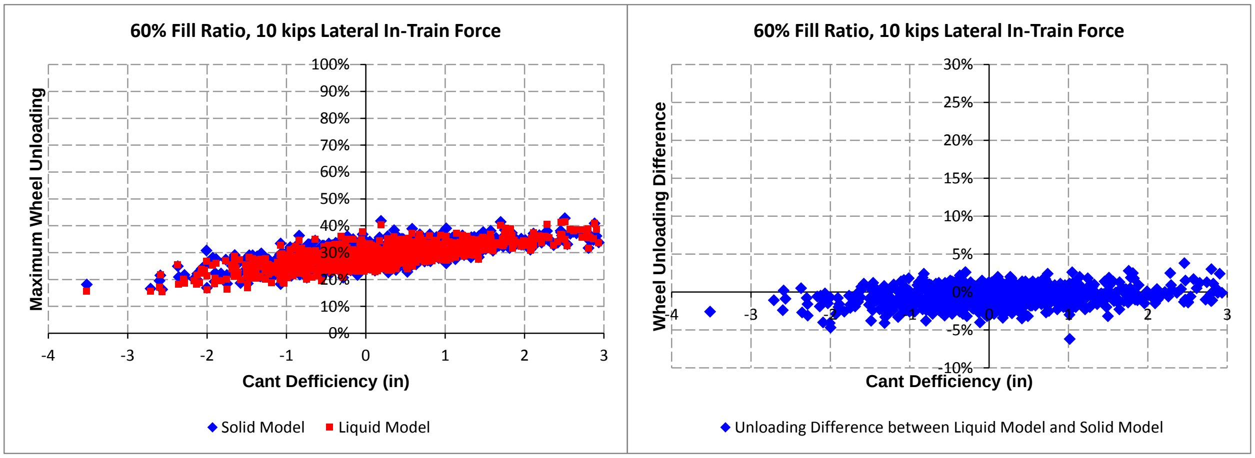


Figure A. 24 Wheel unloading versus cant deficiency at 60% fill ratio and 10 kip lateral in-train force

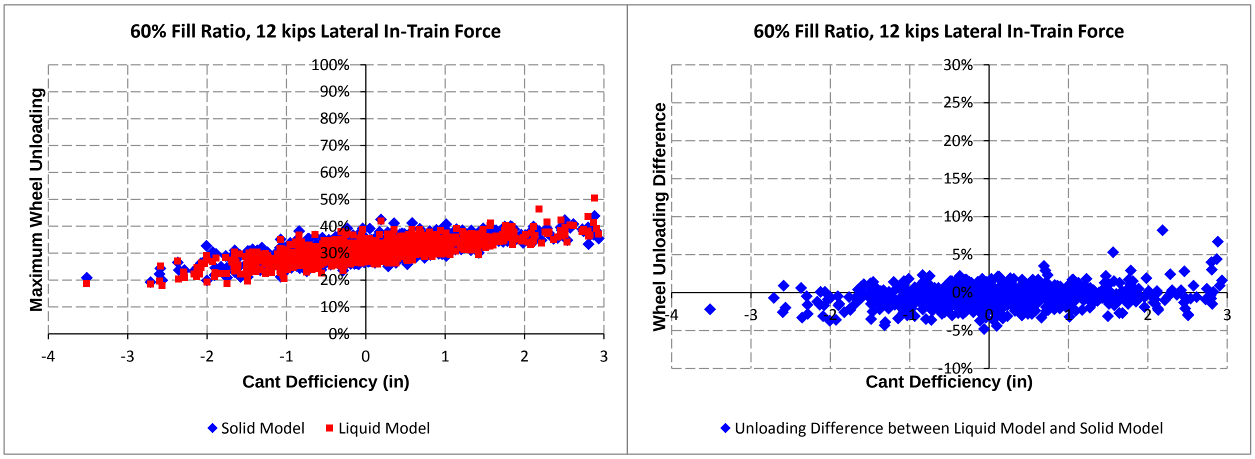


Figure A. 25 Wheel unloading versus cant deficiency at 60% fill ratio and 12 kip lateral in-train force

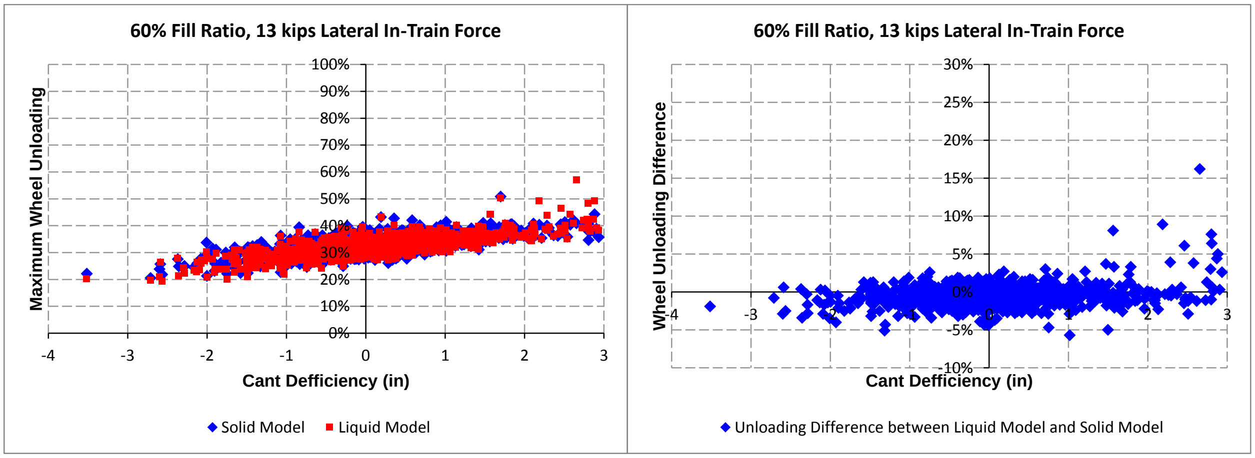


Figure A. 26 Wheel unloading versus cant deficiency at 60% fill ratio and 13 kip lateral in-train force

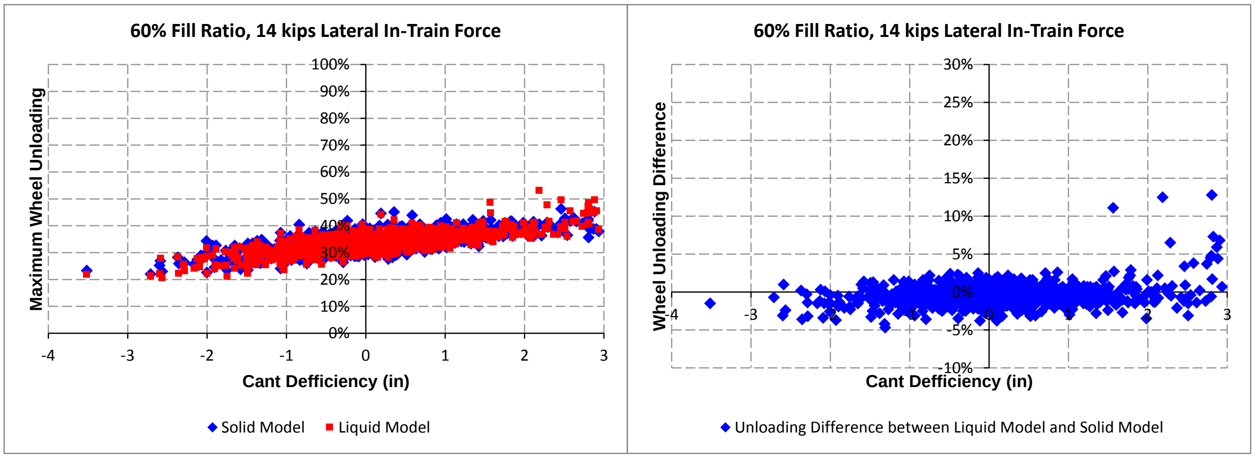


Figure A. 27   Wheel unloading versus cant deficiency at 60% fill ratio and 14 kip lateral in-train force

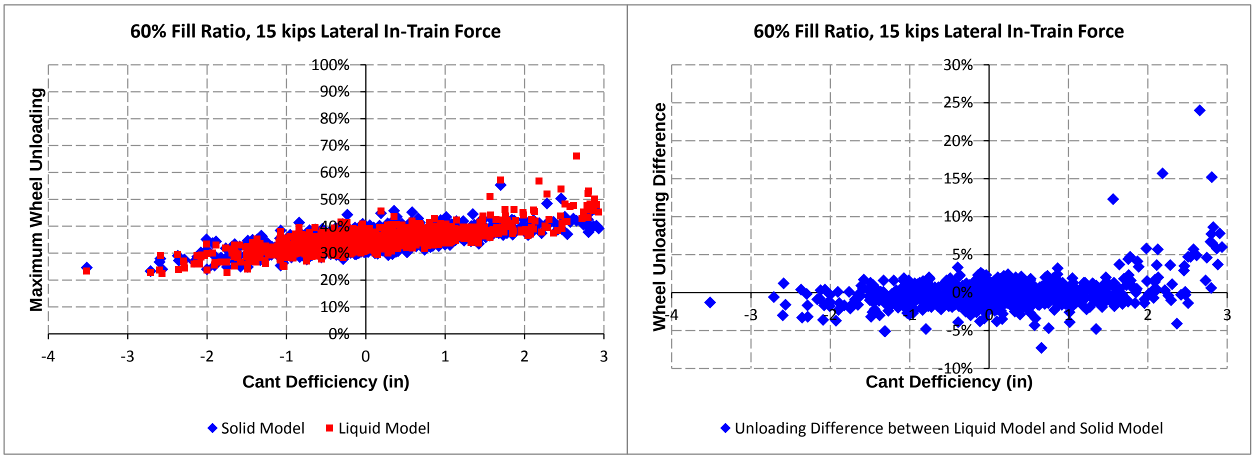


Figure A. 28   Wheel unloading versus cant deficiency at 60% fill ratio and 15 kip lateral in-train force

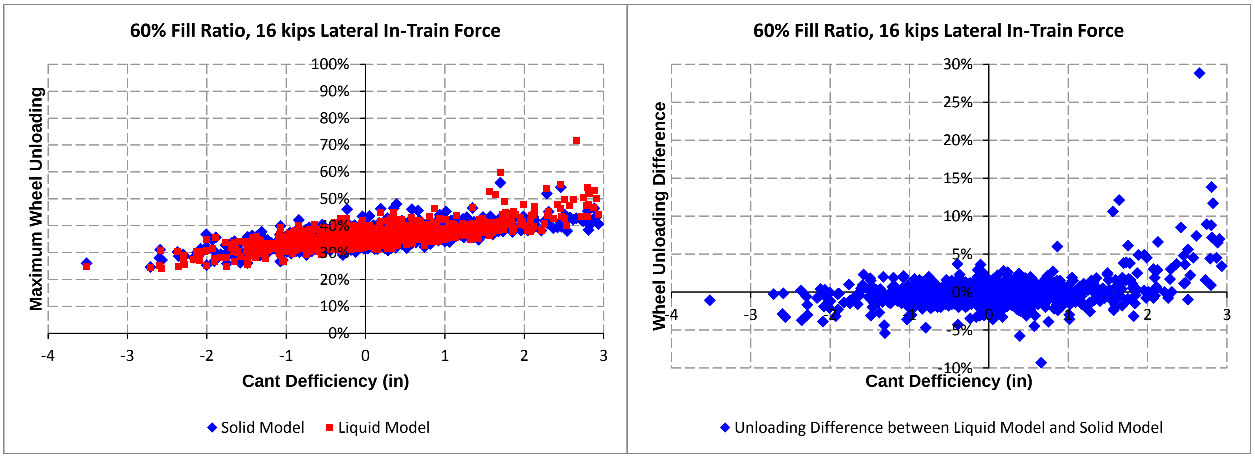


Figure A. 29   Wheel unloading versus cant deficiency at 60% fill ratio and 16 kip lateral in-train force

A.4 Simulation Results at 50% Fill Ratio (50% Outage)

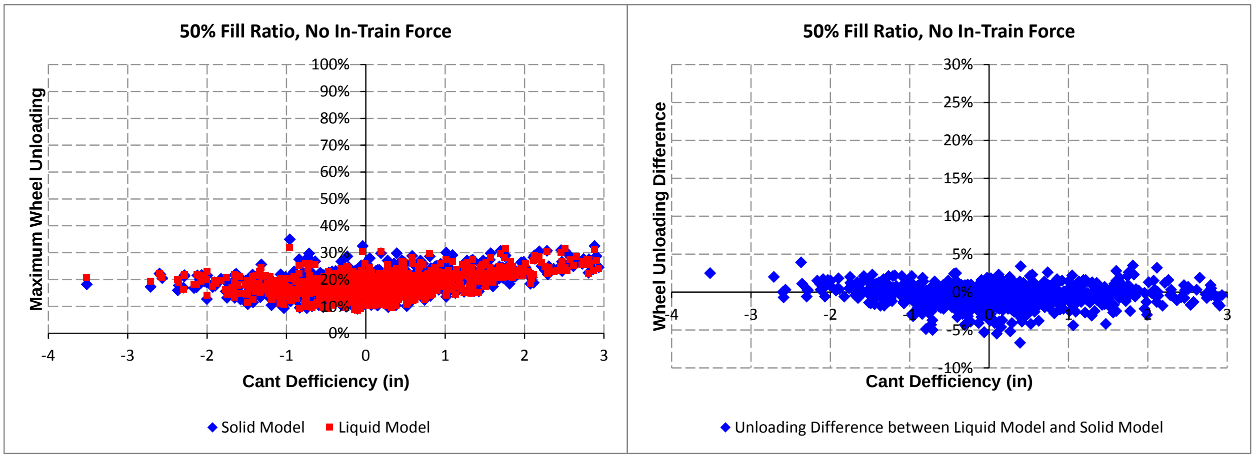


Figure A. 30 Wheel unloading versus cant deficiency at 50% fill ratio and no in-train force

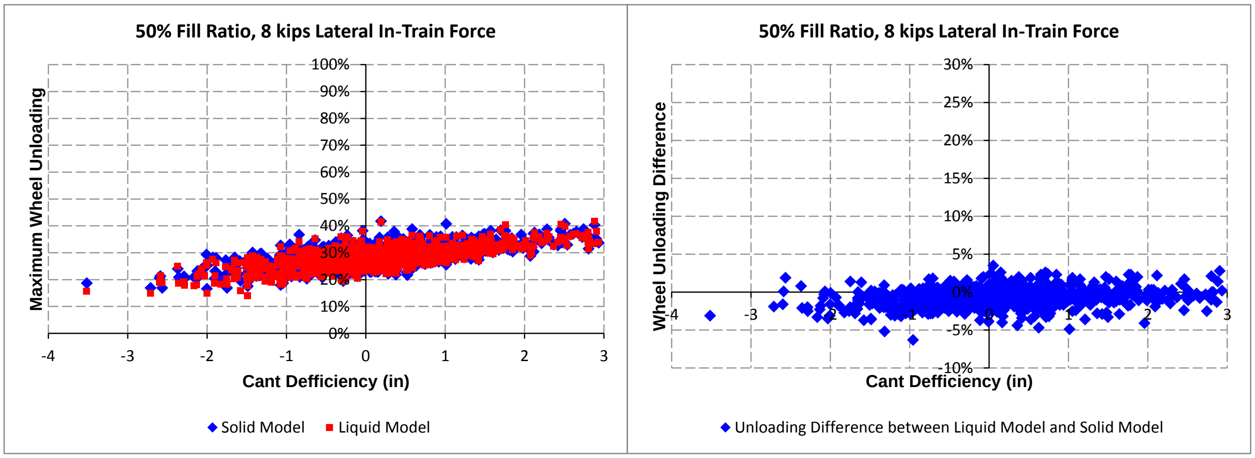


Figure A. 31 Wheel unloading versus cant deficiency at 50% fill ratio and 8 kip lateral in-train force

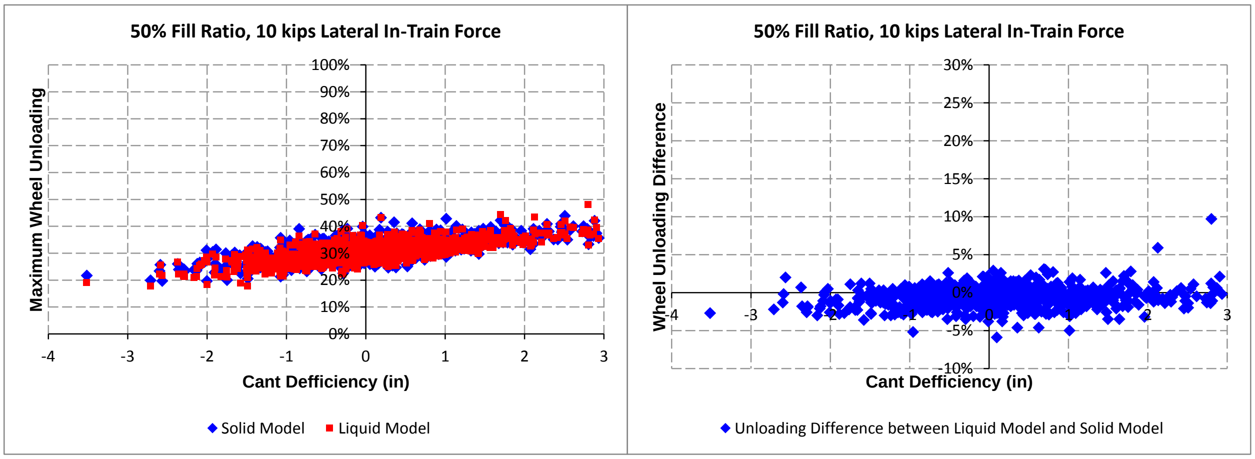


Figure A. 32 Wheel unloading versus cant deficiency at 50% fill ratio and 10 kip lateral in-train force

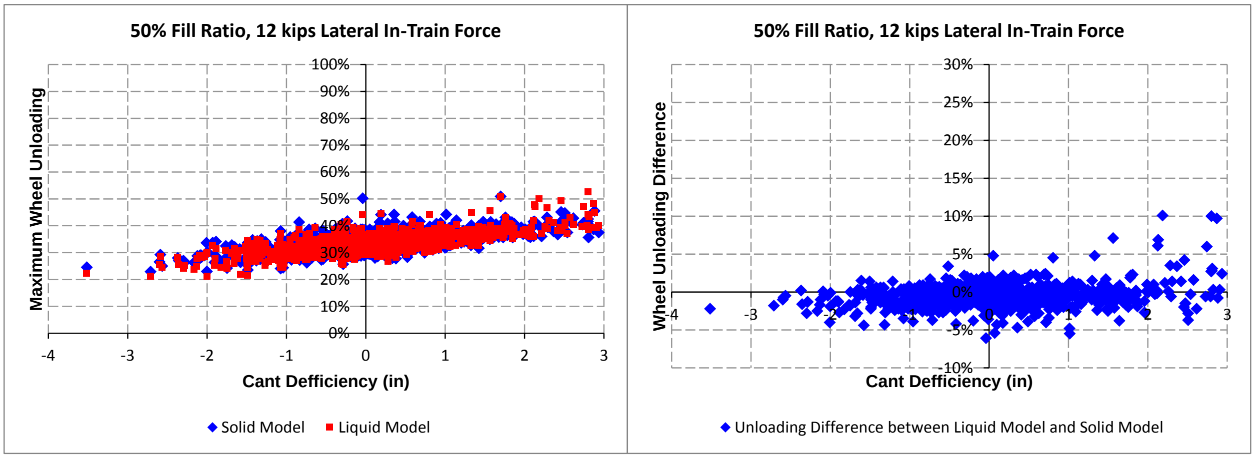


Figure A. 33 Wheel unloading versus cant deficiency at 50% fill ratio and 12 kip lateral in-train force

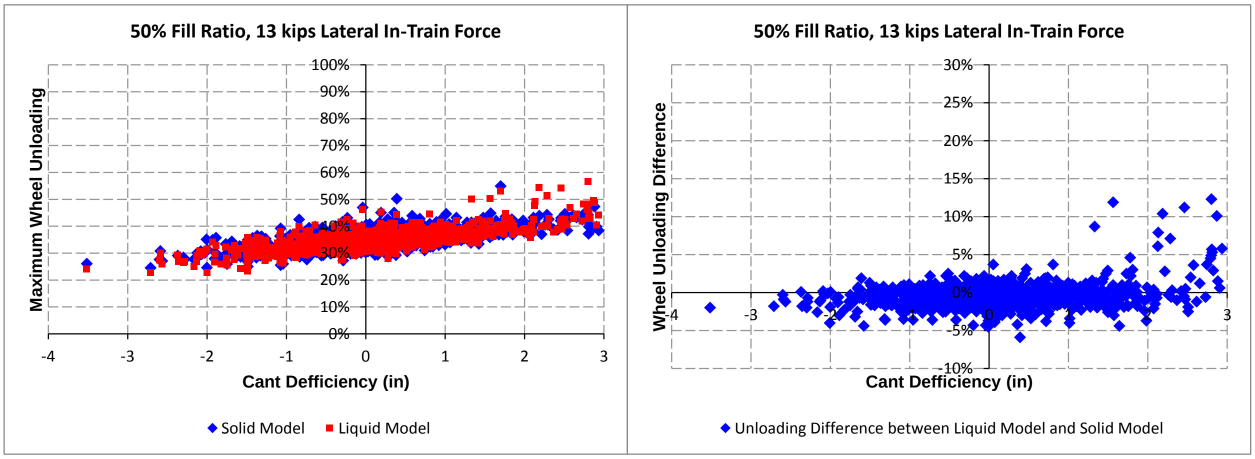


Figure A. 34 Wheel unloading versus cant deficiency at 50% fill ratio and 13 kip lateral in-train force

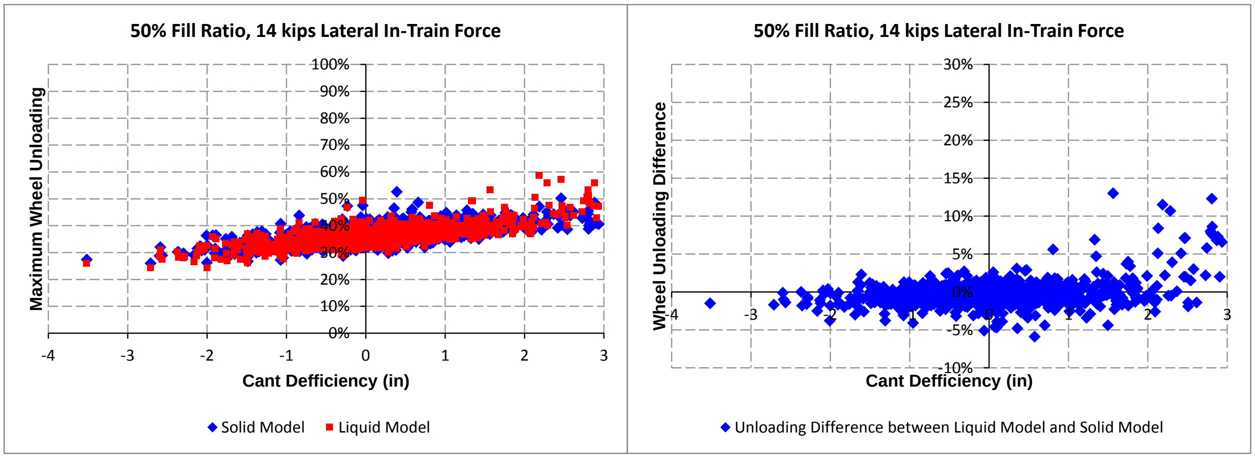


Figure A. 35 Wheel unloading versus cant deficiency at 50% fill ratio and 14 kip lateral in-train force

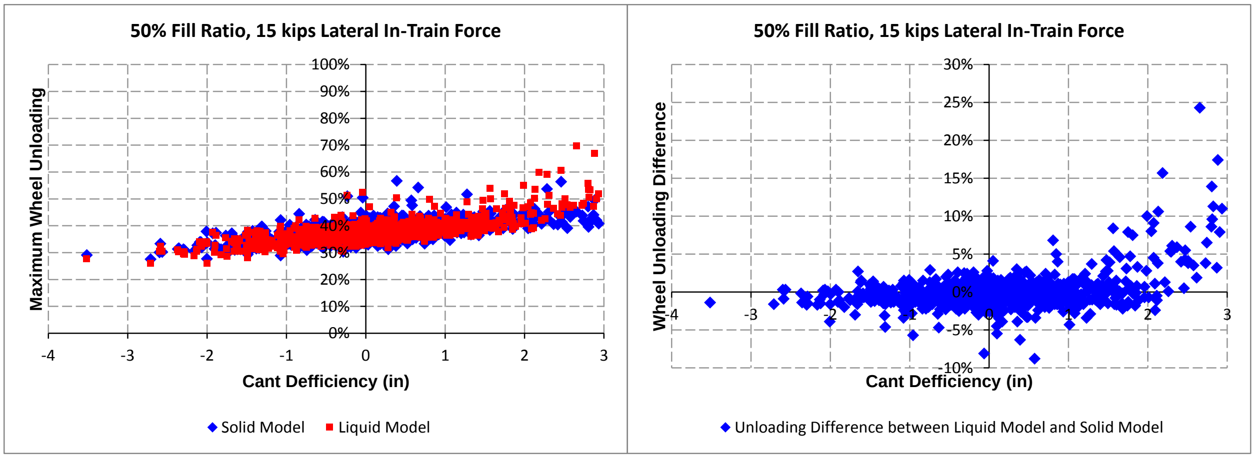


Figure A. 36 Wheel unloading versus cant deficiency at 50% fill ratio and 15 kip lateral in-train force

Appendix B Cumulative Percentage of Wheel Unloading

B.1 80% Fill Ratio (14% Outage)

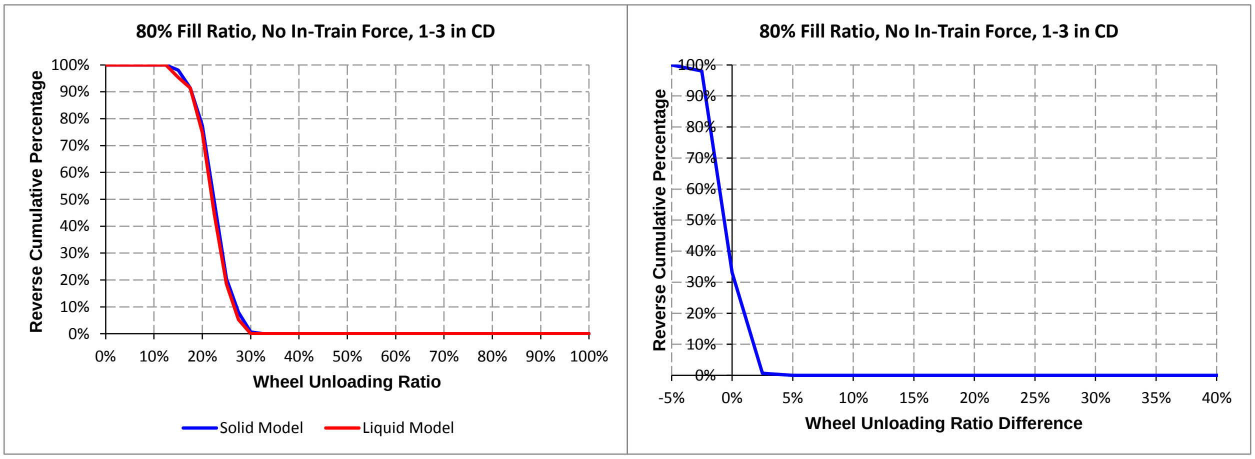


Figure B. 1 Cumulative percentage of wheel unloading at 80% fill ratio, 1 to 3 in cant deficiency and no in-train force

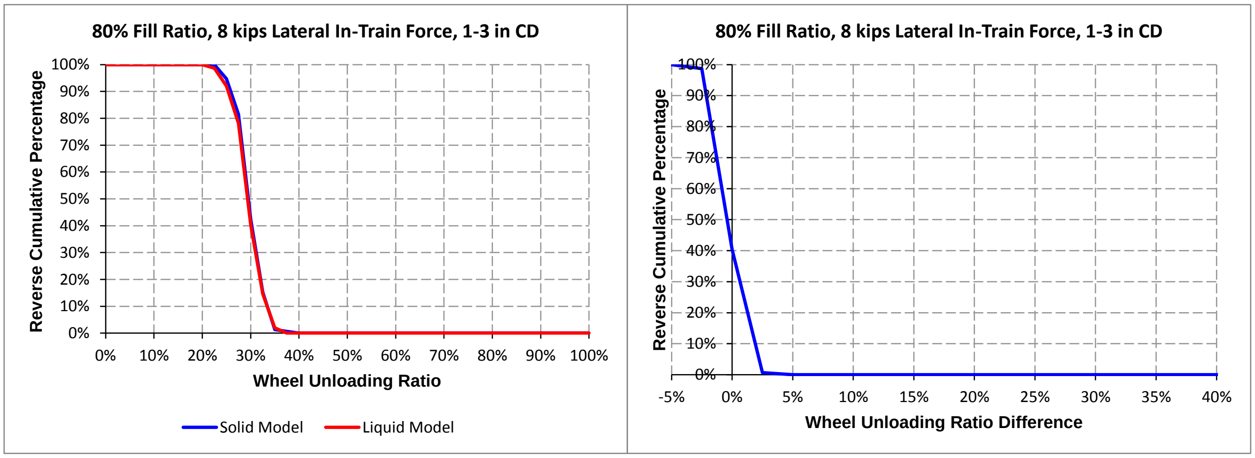


Figure B. 2 Cumulative percentage of wheel unloading at 80% fill ratio, 1 to 3 in cant deficiency and 8 kip lateral in-train force

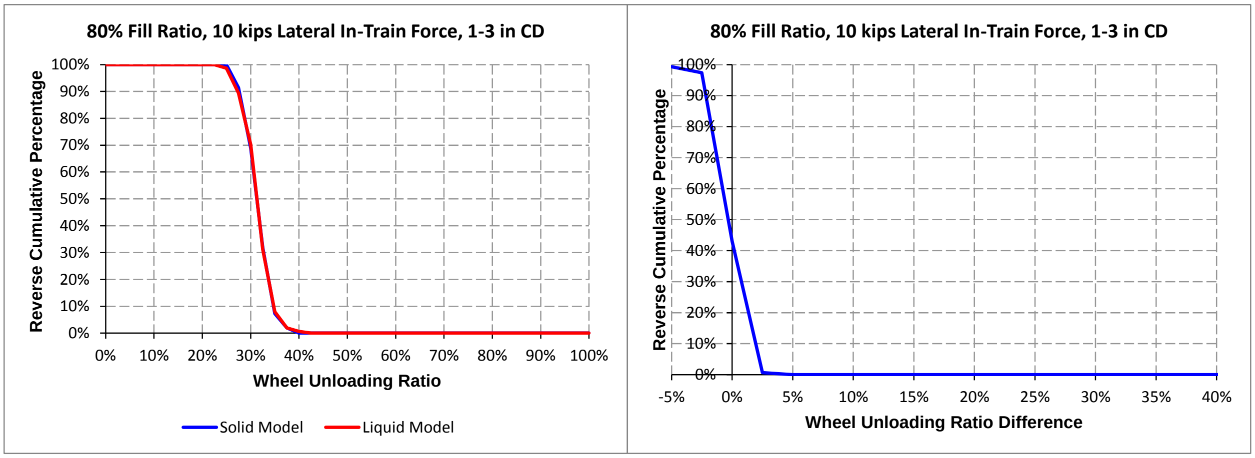


Figure B. 3 Cumulative percentage of wheel unloading at 80% fill ratio, 1 to 3 in. cant deficiency and 10 kip lateral in-train force

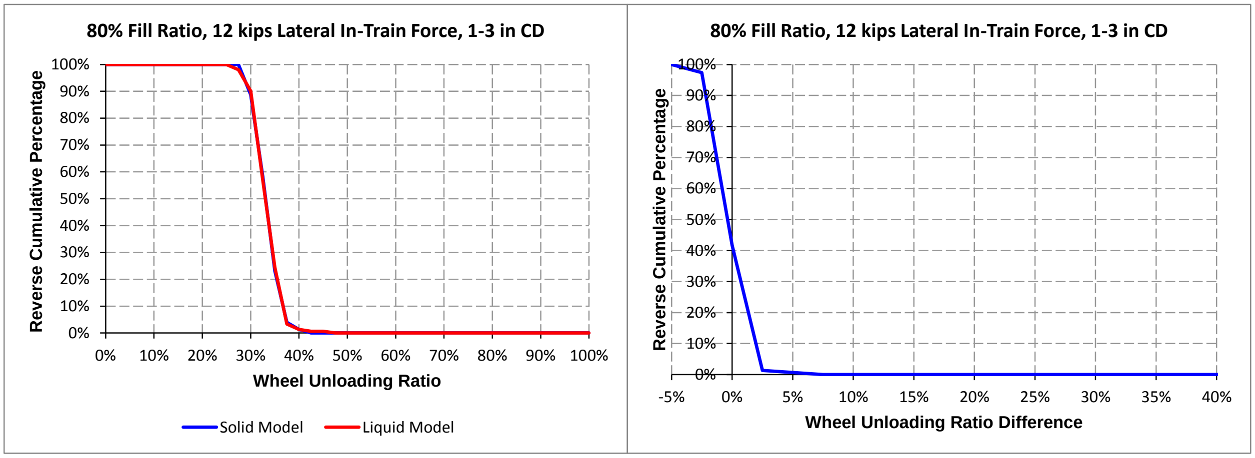


Figure B. 4 Cumulative percentage of wheel unloading at 80% fill ratio, 1 to 3 in. cant deficiency and 12 kip lateral in-train force

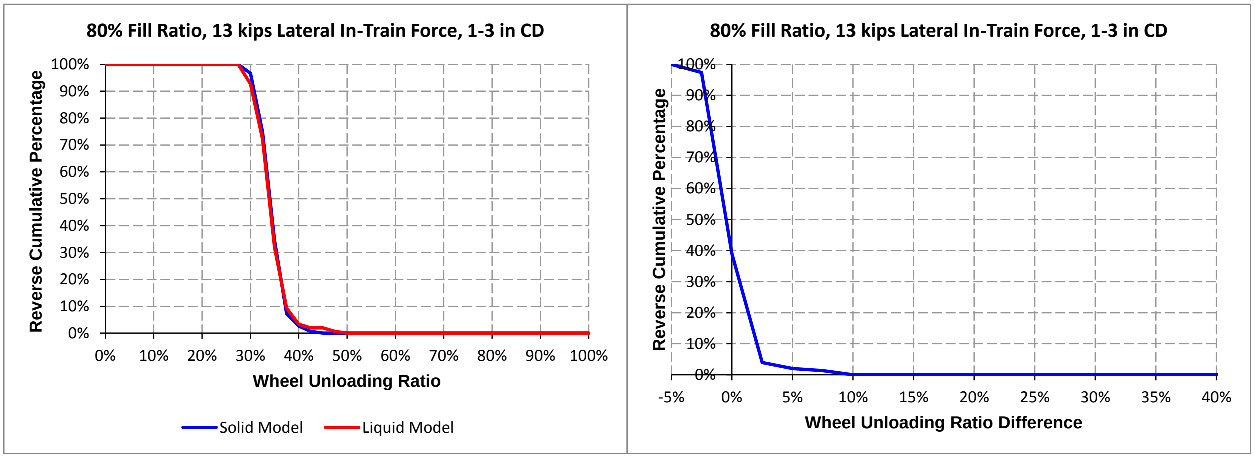


Figure B. 5 Cumulative percentage of wheel unloading at 80% fill ratio, 1 to 3 in. cant deficiency and 13 kip lateral in-train force

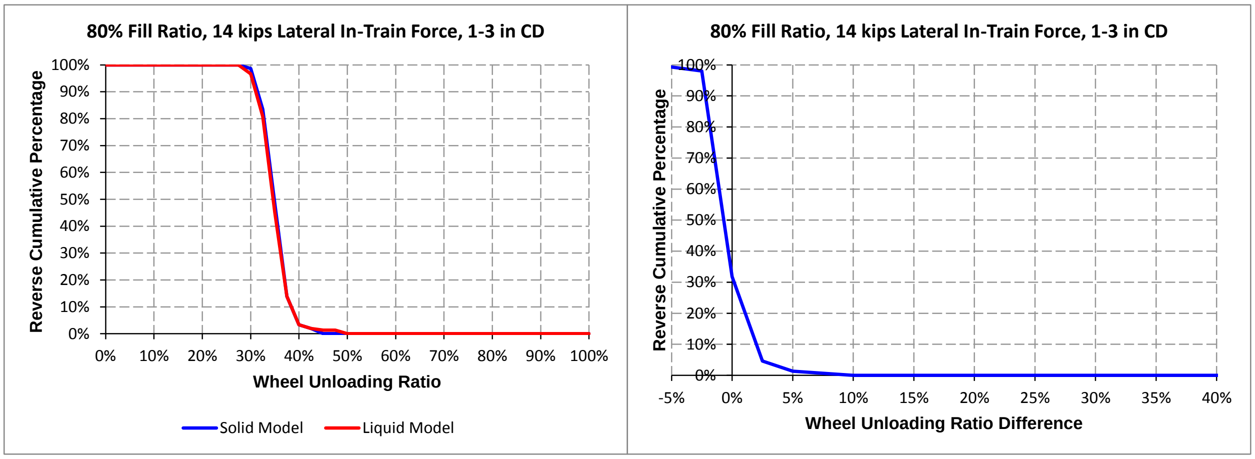


Figure B. 6 Cumulative percentage of wheel unloading at 80% fill ratio, 1 to 3 in. cant deficiency and 14 kip lateral in-train force

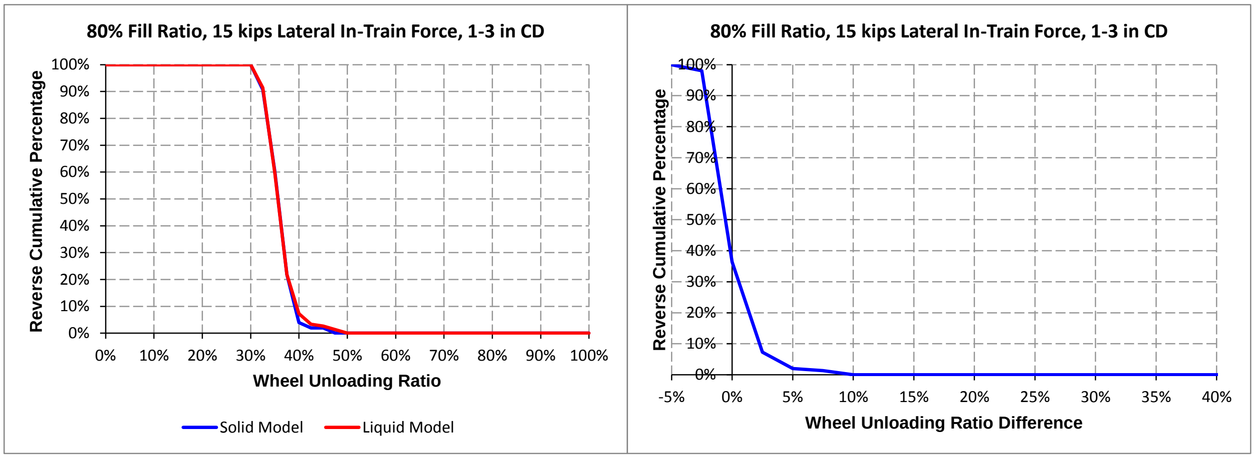


Figure B. 7 Cumulative percentage of wheel unloading at 80% fill ratio, 1 to 3 in. cant deficiency and 15 kip lateral in-train force

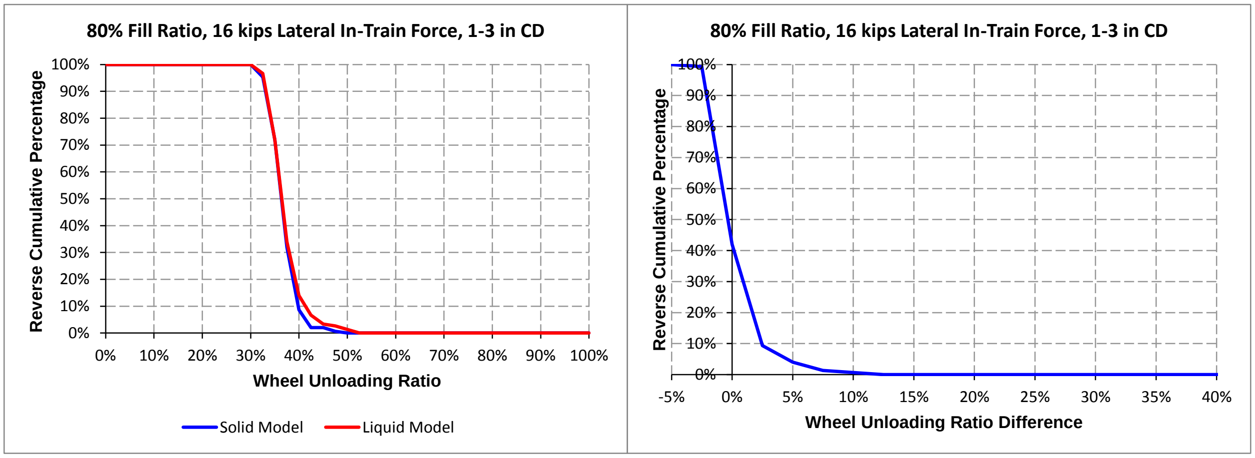


Figure B. 8 Cumulative percentage of wheel unloading at 80% fill ratio, 1 to 3 in. cant deficiency and 16 kip lateral in-train force

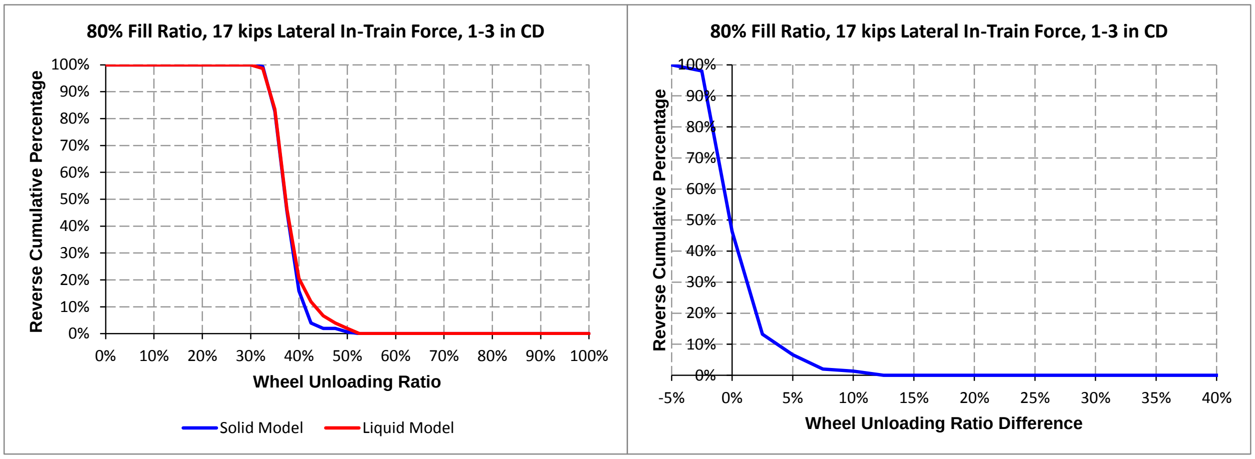


Figure B. 9 Cumulative percentage of wheel unloading at 80% fill ratio, 1 to 3 in. cant deficiency and 17 kip lateral in-train force

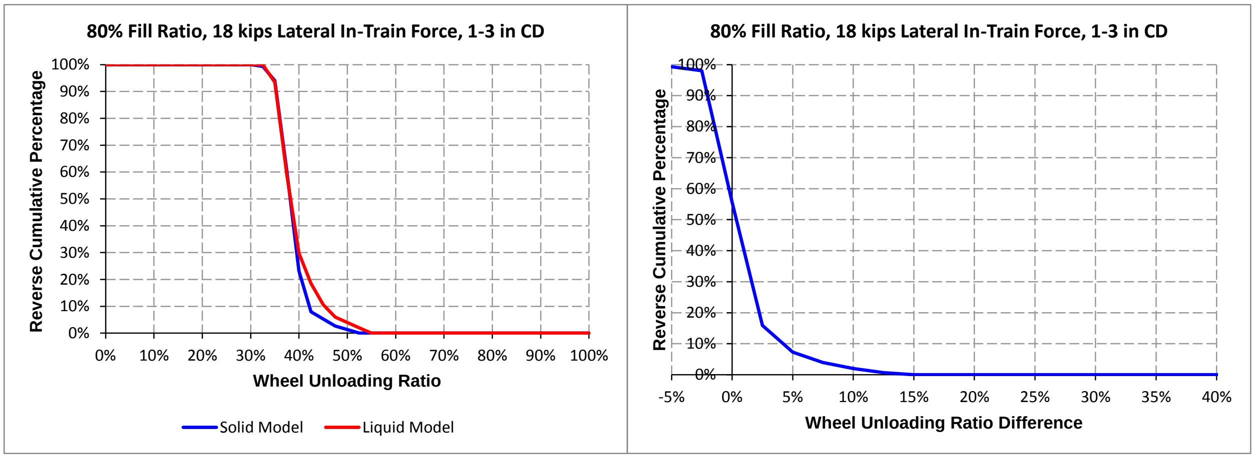


Figure B. 10 Cumulative percentage of wheel unloading at 80% fill ratio, 1 to 3 in cant deficiency and 18 kip lateral in-train force

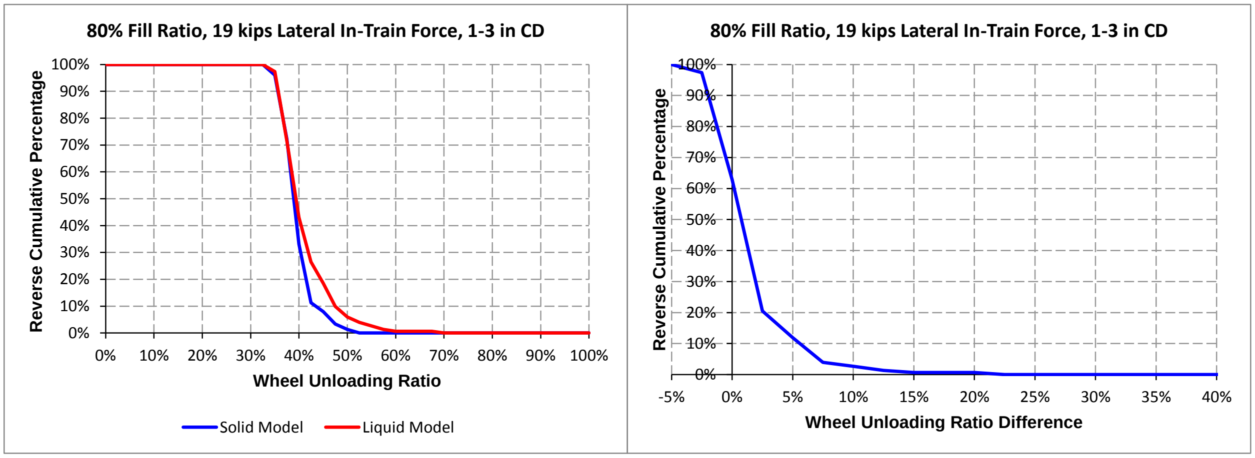


Figure B. 11 Cumulative percentage of wheel unloading at 80% fill ratio, 1 to 3 in. cant deficiency and 19 kip lateral in-train force

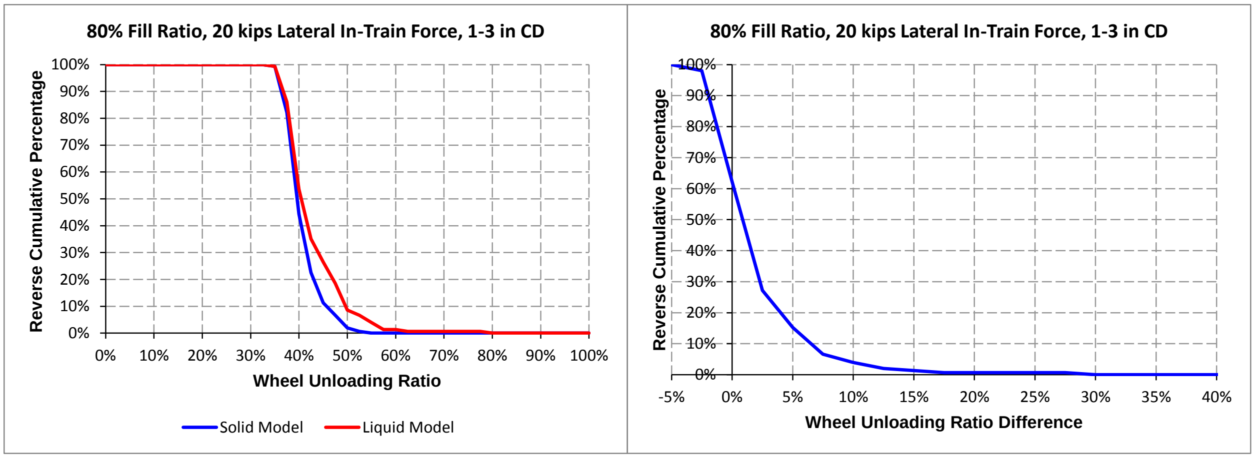


Figure B. 12 Cumulative percentage of wheel unloading at 80% fill ratio, 1 to 3 in. cant deficiency and 20 kip lateral in-train force

B.2 70% Fill Ratio (25% Outage)

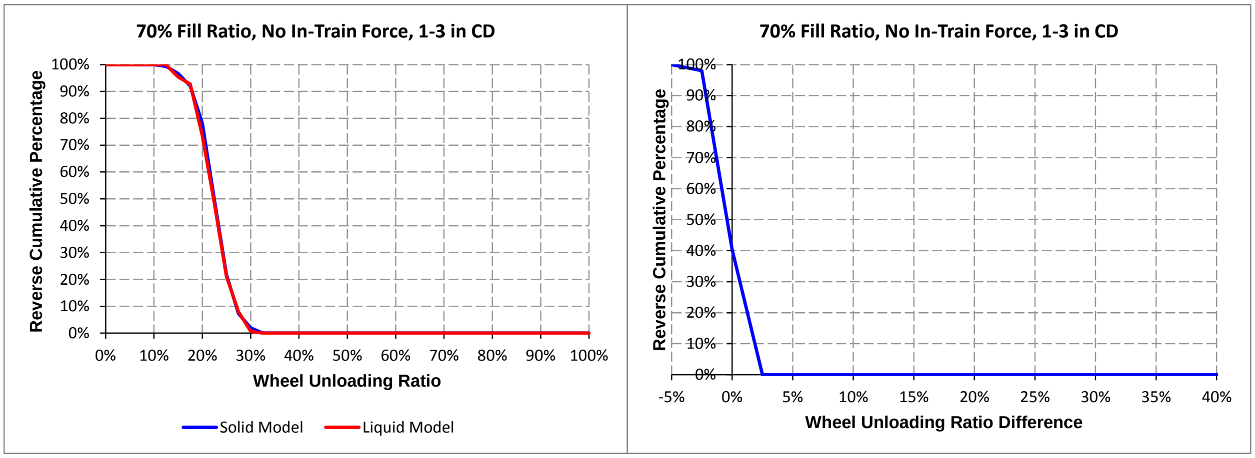


Figure B. 13 Cumulative percentage of wheel unloading at 70% fill ratio, 1 to 3 in. cant deficiency and no in-train force

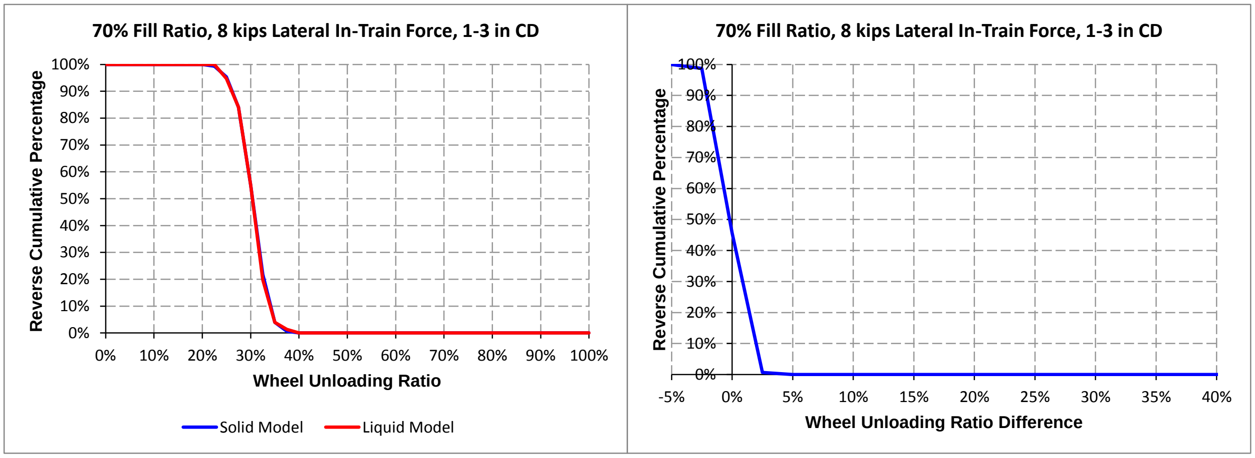
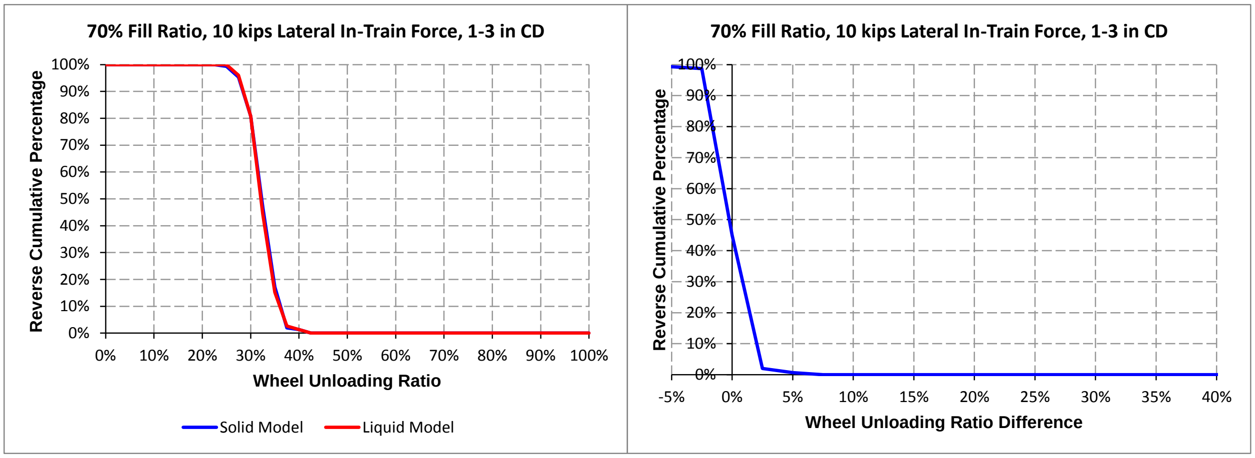
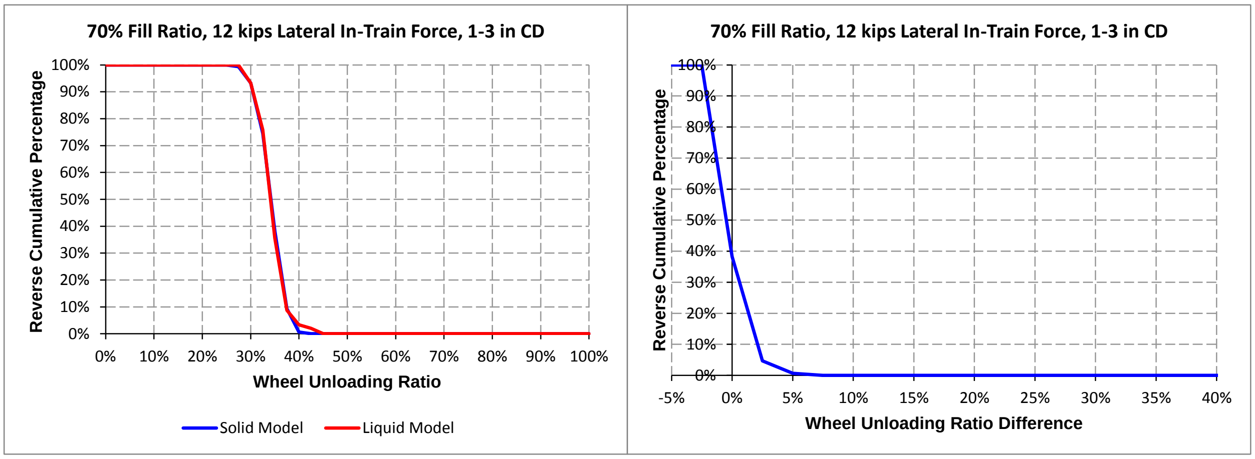


Figure B. 14 Cumulative percentage of wheel unloading at 70% fill ratio, 1 to 3 in. cant deficiency and 8 kip lateral in-train force


70% Fill Ratio, 10 kips Lateral In-Train Force, 1-3 in CD

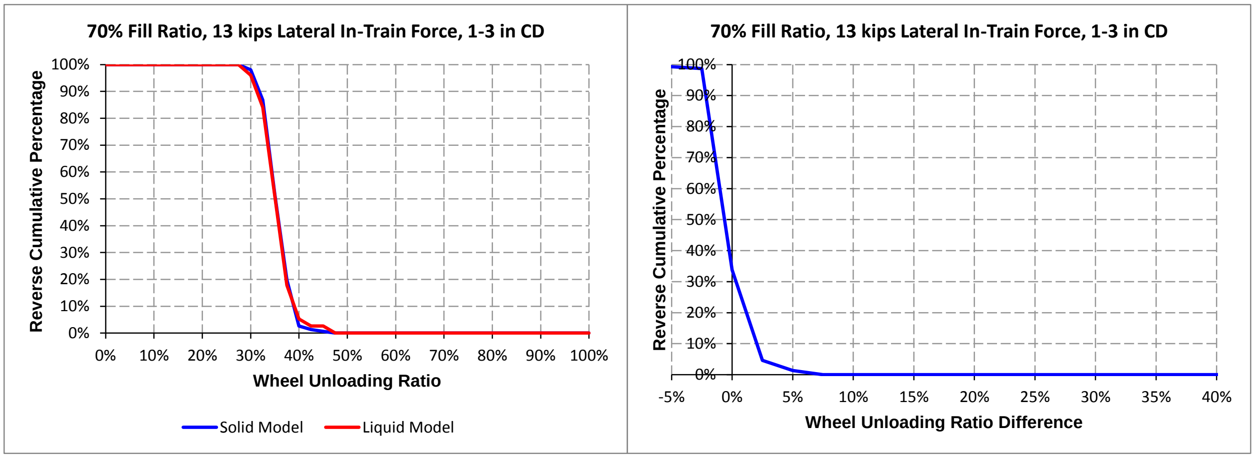
70% Fill Ratio, 10 kips Lateral In-Train Force, 1-3 in CD

Figure B. 15 Cumulative percentage of wheel unloading at 70% fill ratio, 1 to 3 in. cant deficiency and 10 kip lateral in-train force


70% Fill Ratio, 12 kips Lateral In-Train Force, 1-3 in CD

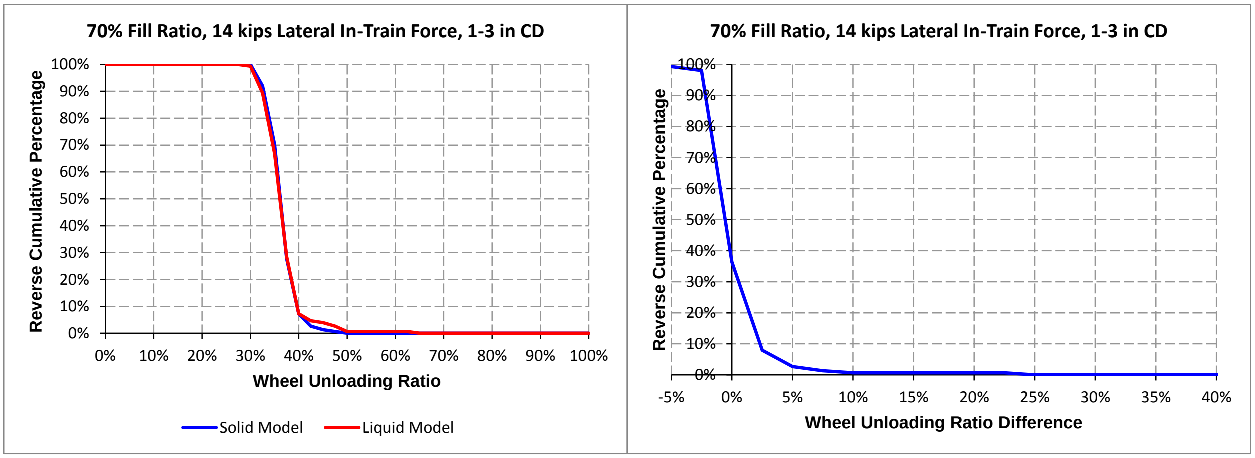
70% Fill Ratio, 12 kips Lateral In-Train Force, 1-3 in CD

Figure B. 16 Cumulative percentage of wheel unloading at 70% fill ratio, 1 to 3 in. cant deficiency and 12 kip lateral in-train force


70% Fill Ratio, 13 kips Lateral In-Train Force, 1-3 in CD

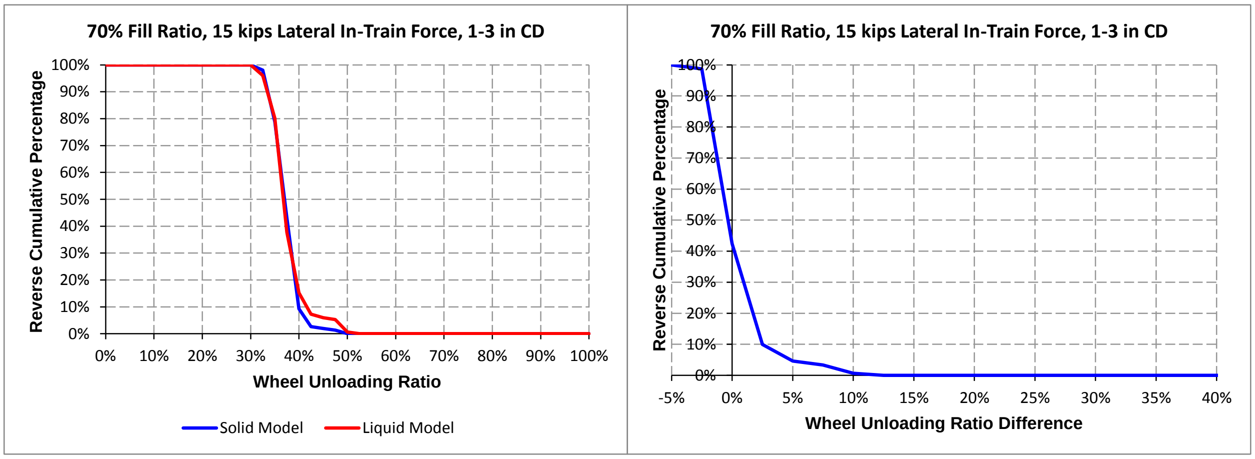
70% Fill Ratio, 13 kips Lateral In-Train Force, 1-3 in CD

Figure B. 17 Cumulative percentage of wheel unloading at 70% fill ratio, 1 to 3 in. cant deficiency and 13 kip lateral in-train force


70% Fill Ratio, 14 kips Lateral In-Train Force, 1-3 in CD

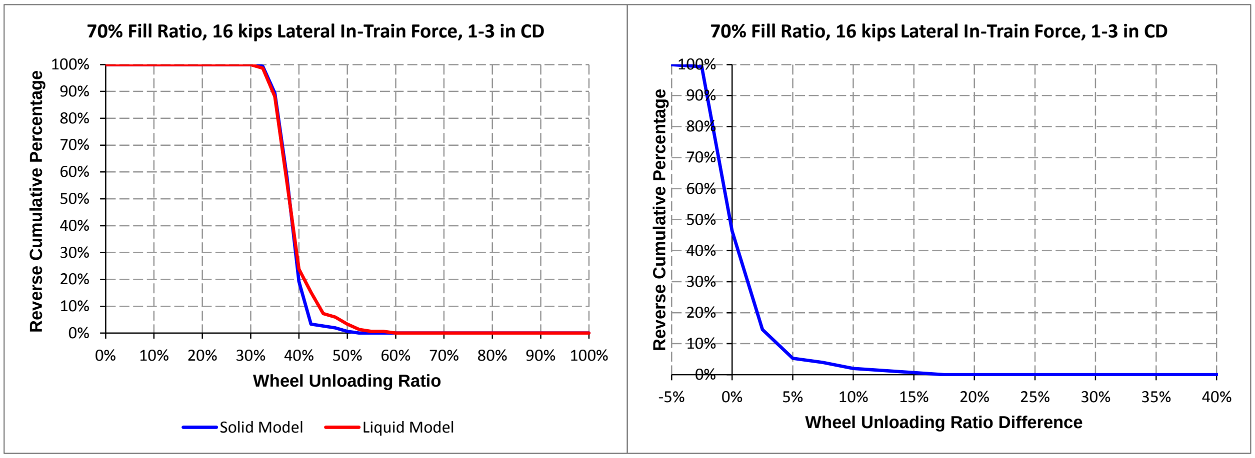
70% Fill Ratio, 14 kips Lateral In-Train Force, 1-3 in CD

Figure B. 18 Cumulative percentage of wheel unloading at 70% fill ratio, 1 to 3 in. cant deficiency and 14 kip lateral in-train force


70% Fill Ratio, 15 kips Lateral In-Train Force, 1-3 in CD

70% Fill Ratio, 15 kips Lateral In-Train Force, 1-3 in CD

Figure B. 19 Cumulative percentage of wheel unloading at 70% fill ratio, 1 to 3 in. cant deficiency and 15 kip lateral in-train force


70% Fill Ratio, 16 kips Lateral In-Train Force, 1-3 in CD

70% Fill Ratio, 16 kips Lateral In-Train Force, 1-3 in CD

Figure B. 20 Cumulative percentage of wheel unloading at 70% fill ratio, 1 to 3 in. cant deficiency and 16 kip lateral in-train force

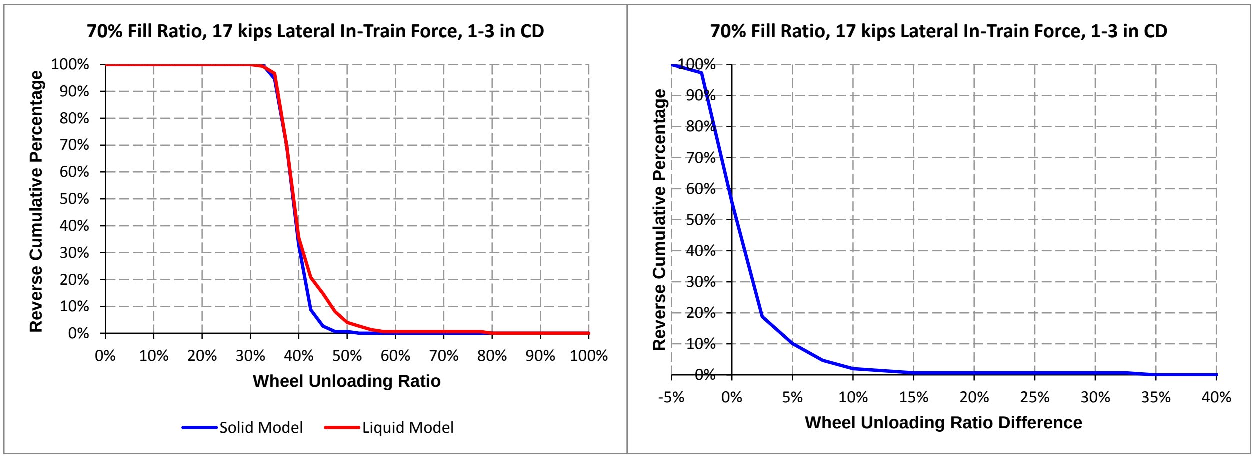


Figure B. 21 Cumulative percentage of wheel unloading at 70% fill ratio, 1 to 3 in. cant deficiency and 17 kip lateral in-train force

B.3 60% Fill Ratio (37% Outage)

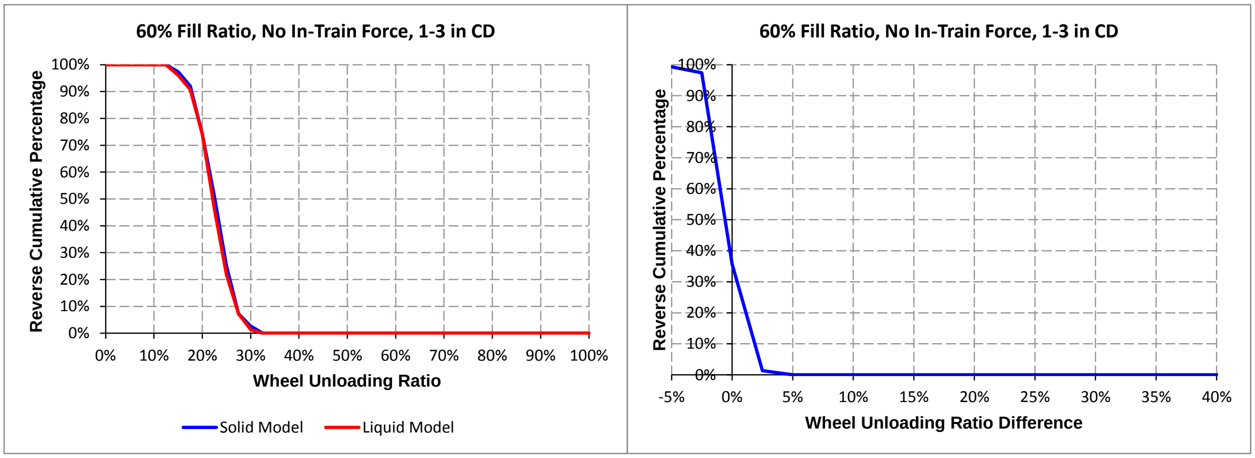


Figure B. 22 Cumulative percentage of wheel unloading at 60% fill ratio, 1 to 3 in. cant deficiency and no in-train force

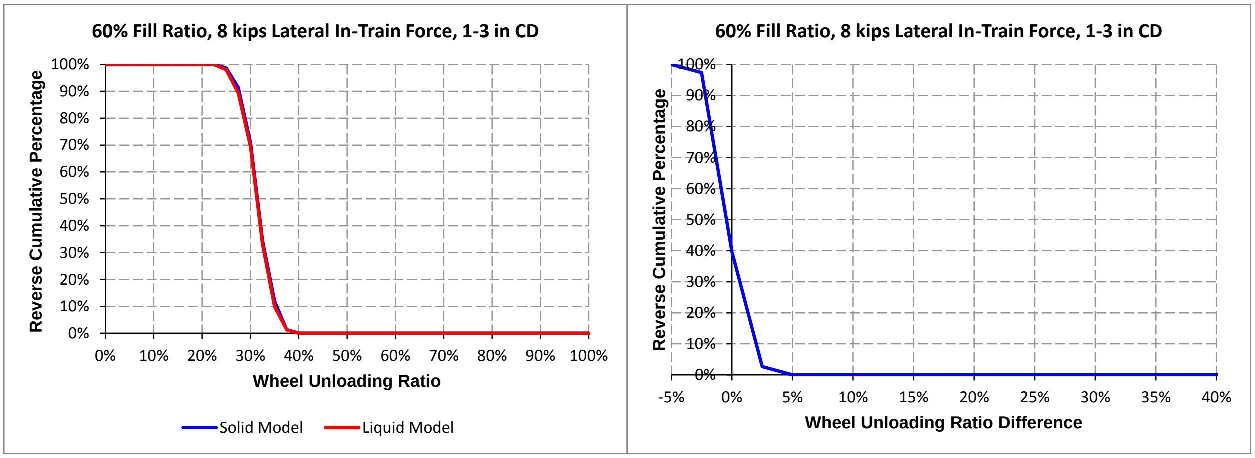


Figure B. 23 Cumulative percentage of wheel unloading at 60% fill ratio, 1 to 3 in. cant deficiency and 8 kip lateral in-train force

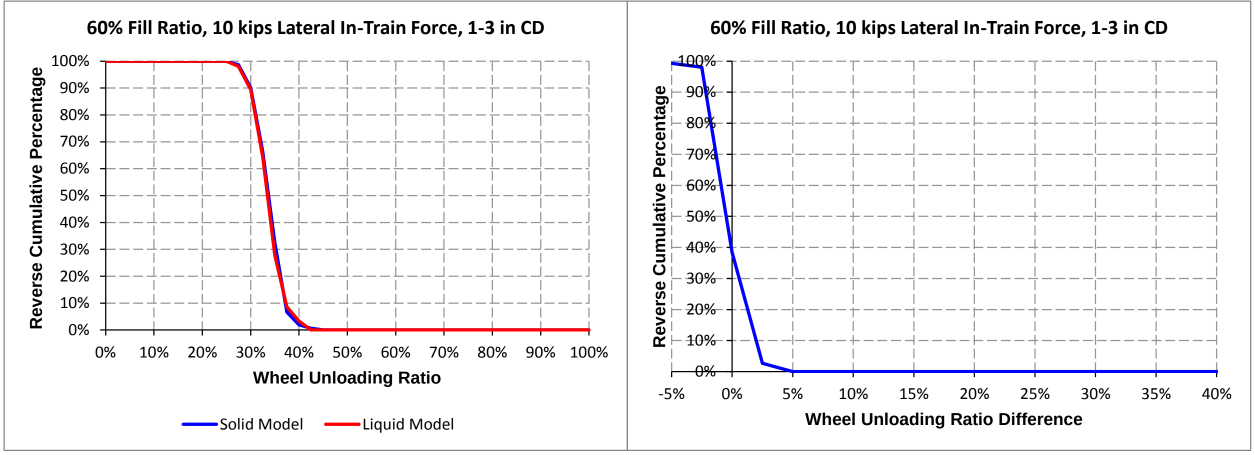


Figure B. 24 Cumulative percentage of wheel unloading at 60% fill ratio, 1 to 3 in. cant deficiency and 10 kip lateral in-train force

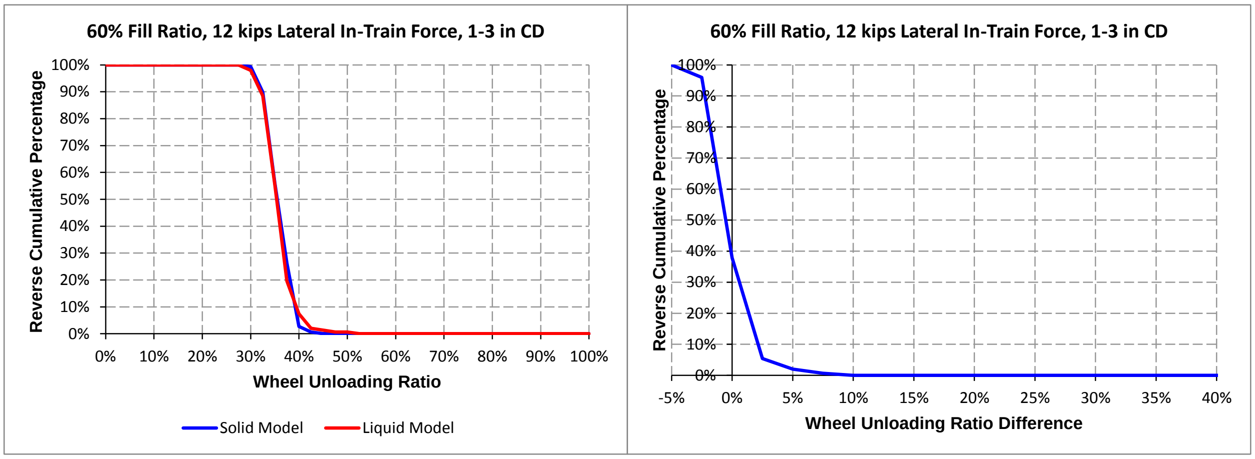


Figure B. 25 Cumulative percentage of wheel unloading at 60% fill ratio, 1 to 3 in. cant deficiency and 12 kip lateral in-train force

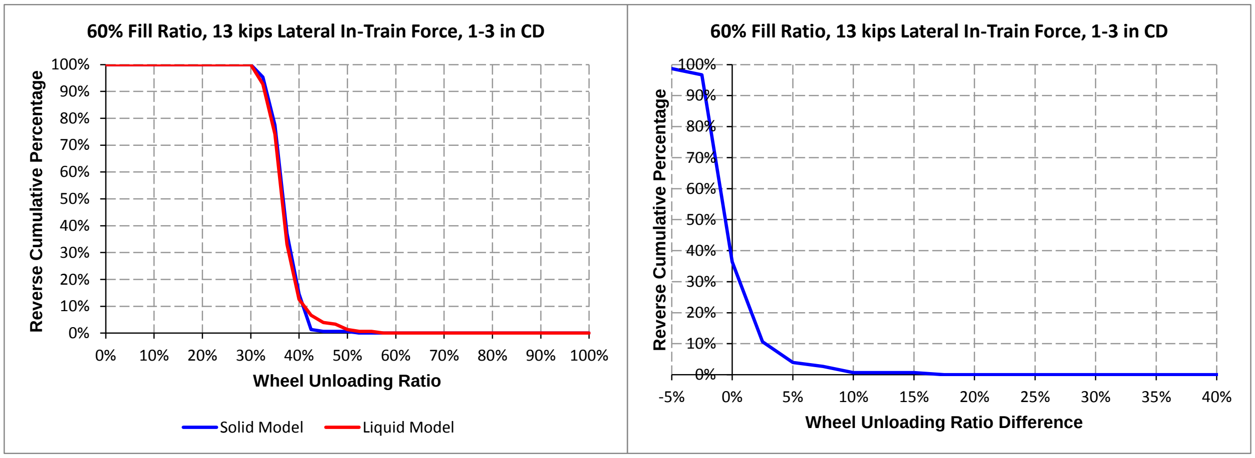


Figure B. 26 Cumulative percentage of wheel unloading at 60% fill ratio, 1 to 3 in. cant deficiency and 13 kip lateral in-train force

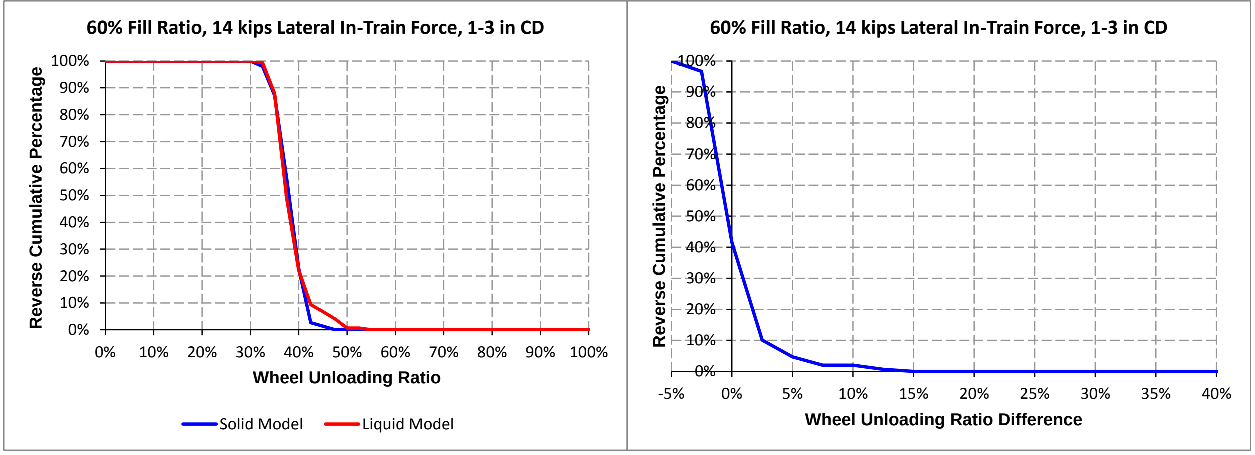


Figure B. 27 Cumulative percentage of wheel unloading at 60% fill ratio, 1 to 3 in. cant deficiency and 14 kip lateral in-train force

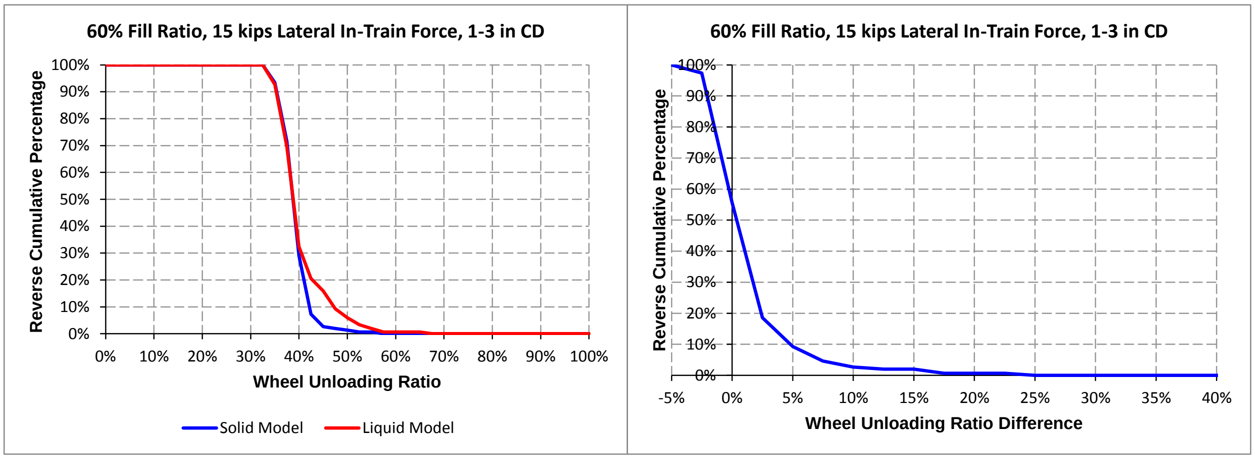


Figure B. 28 Cumulative percentage of wheel unloading at 60% fill ratio, 1 to 3 in. cant deficiency and 15 kip lateral in-train force

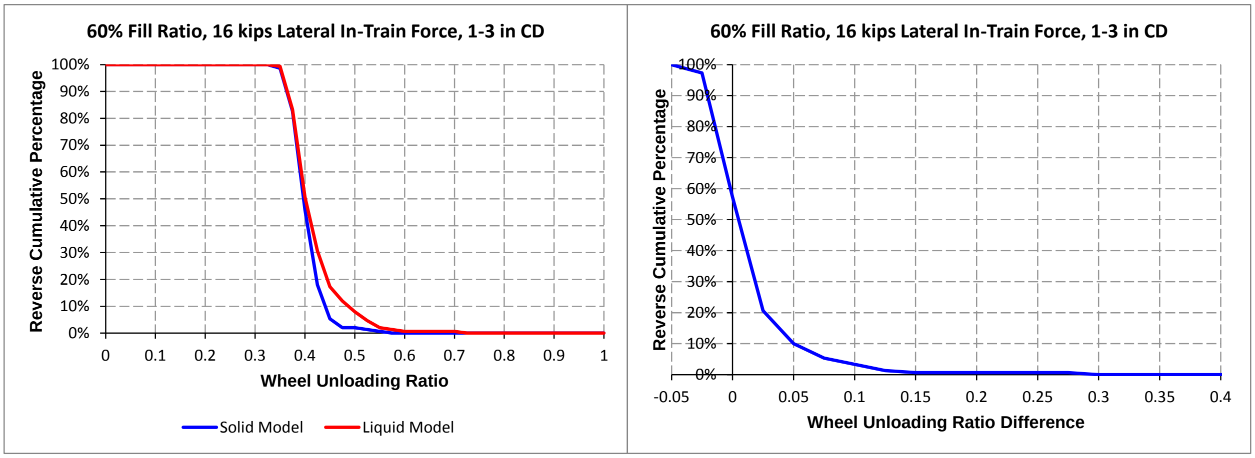


Figure B. 29 Cumulative percentage of wheel unloading at 60% fill ratio, 1 to 3 in. cant deficiency and 16 kip lateral in-train force

B.4 50% Fill Ratio (50% Outage)

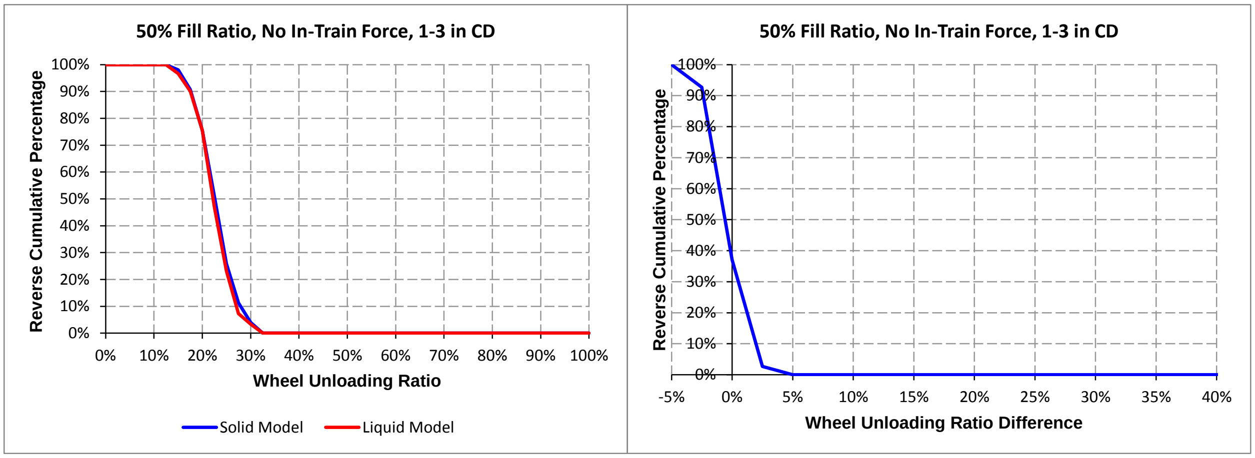


Figure B. 30 Cumulative percentage of wheel unloading at 50% fill ratio, 1 to 3 in. cant deficiency and no in-train force

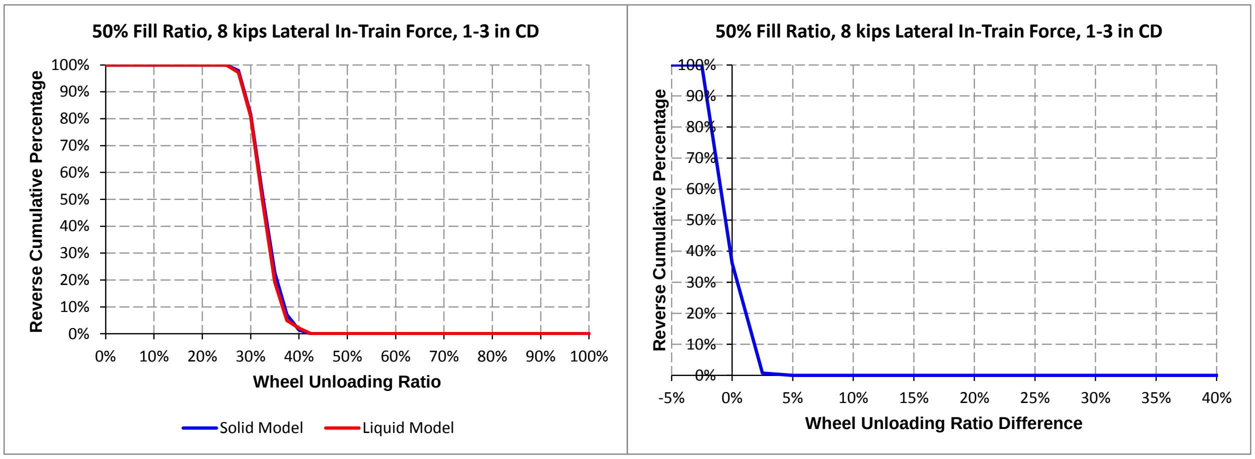


Figure B. 31 Cumulative percentage of wheel unloading at 50% fill ratio, 1 to 3 in. cant deficiency and 8 kip lateral in-train force

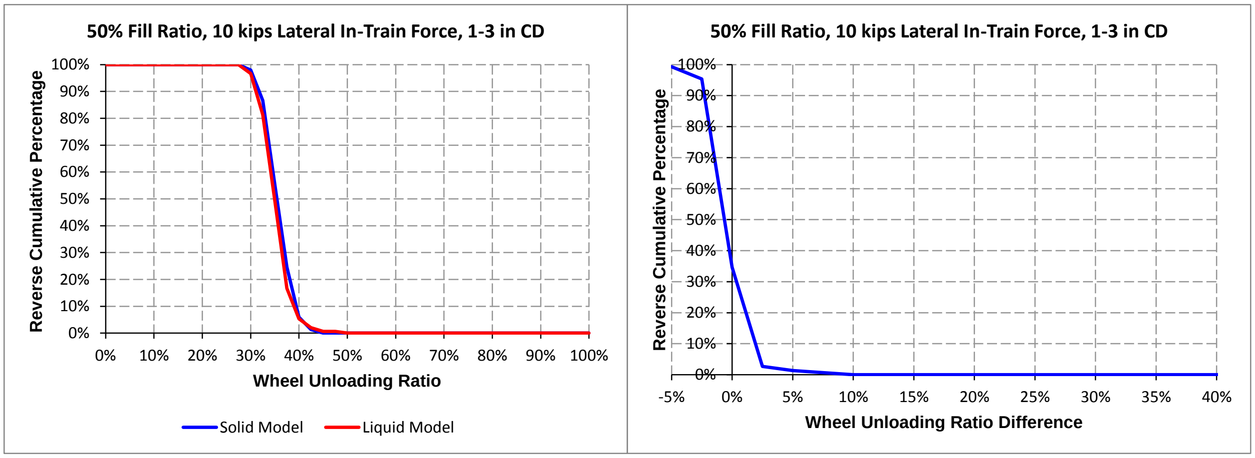


Figure B. 32 Cumulative percentage of wheel unloading at 50% fill ratio, 1 to 3 in. cant deficiency and 10 kip lateral in-train force

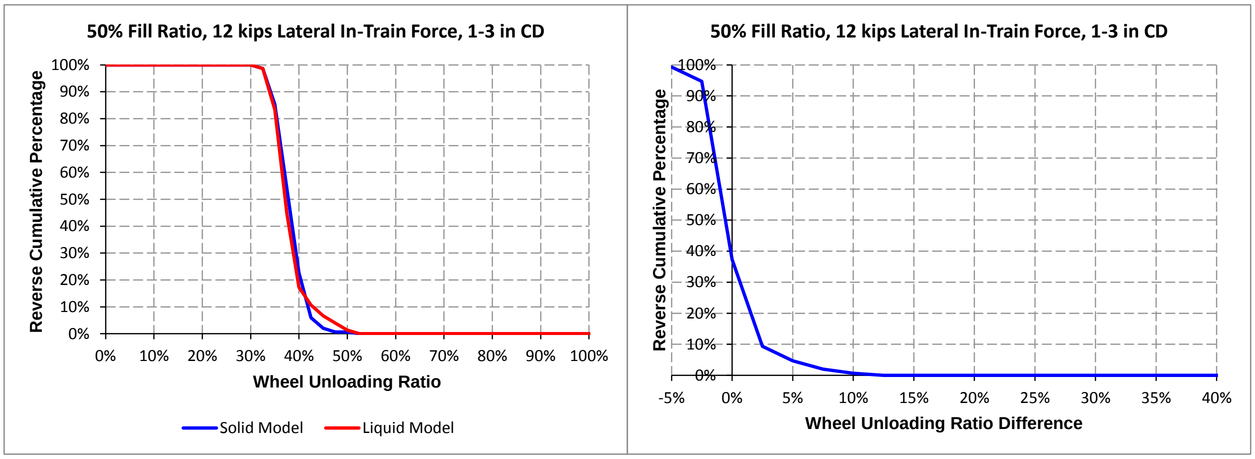


Figure B. 33 Cumulative percentage of wheel unloading at 50% fill ratio, 1 to 3 in. cant deficiency and 12 kip lateral in-train force

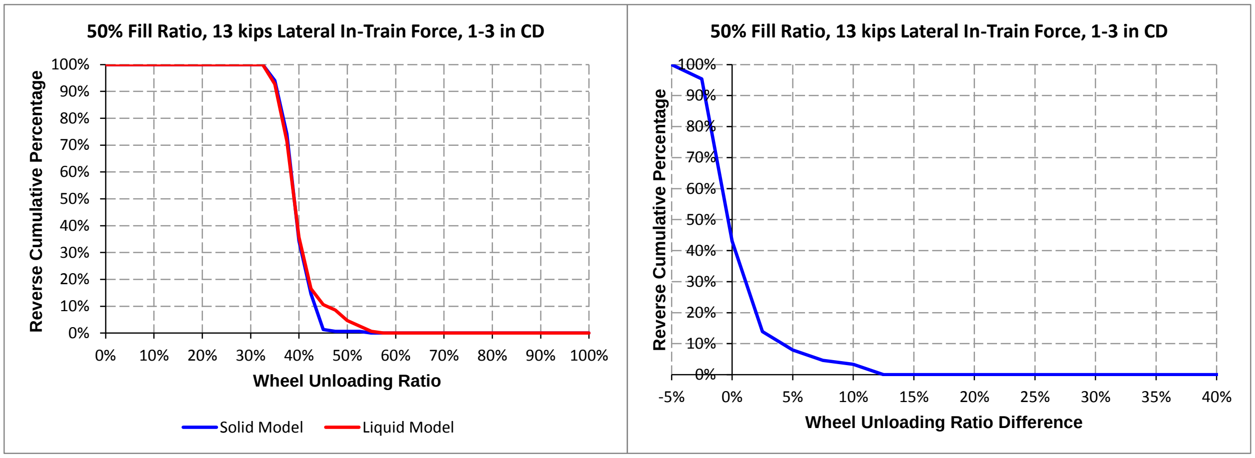


Figure B. 34 Cumulative percentage of wheel unloading at 50% fill ratio, 1 to 3 in. cant deficiency and 13 kip lateral in-train force

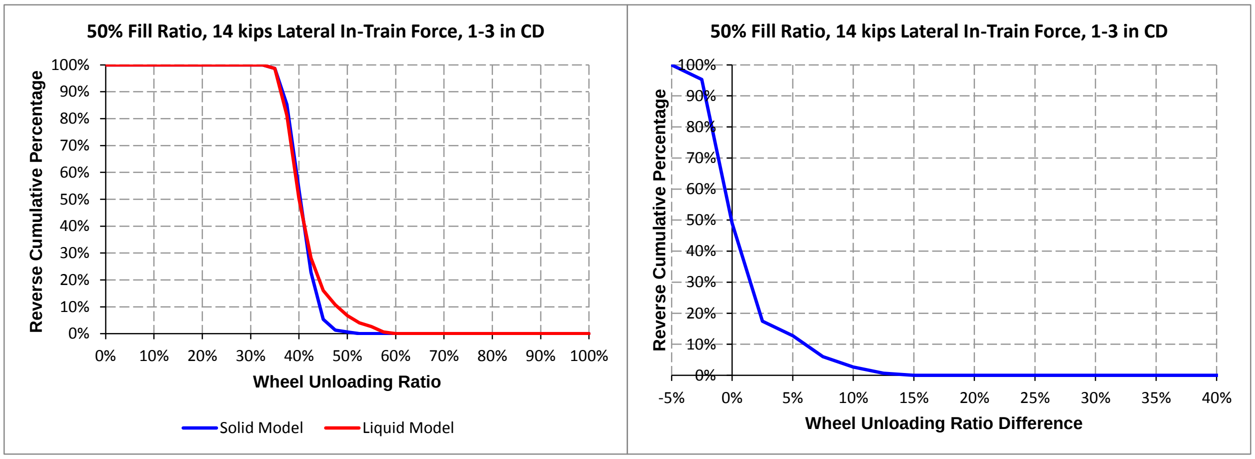


Figure B. 35 Cumulative percentage of wheel unloading at 50% fill ratio, 1 to 3 in. cant deficiency and 14 kip lateral in-train force

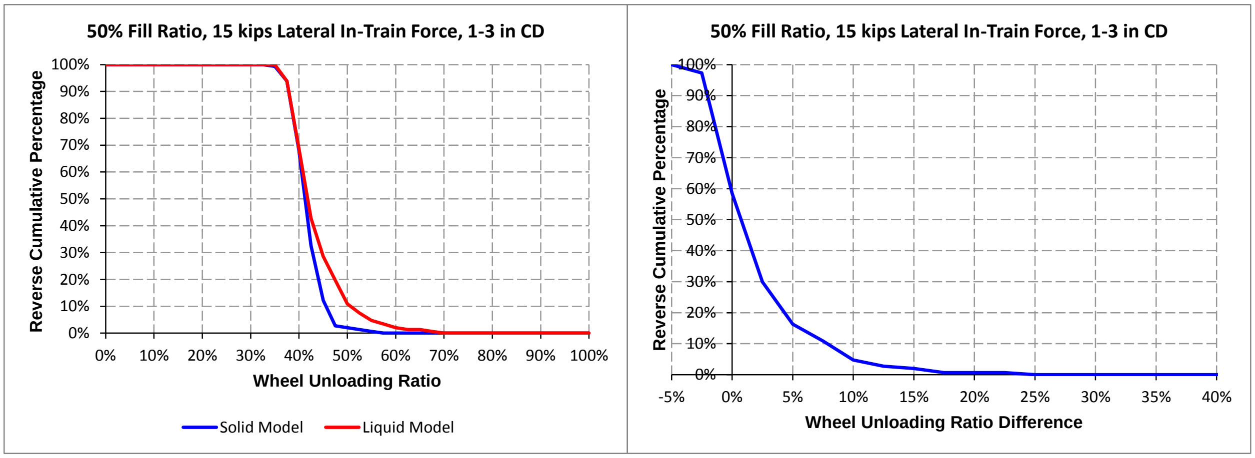


Figure B. 36 **Cumulative percentage of wheel unloading at 50% fill ratio, 1 to 3 in. cant deficiency and 15 kip lateral in-train force**